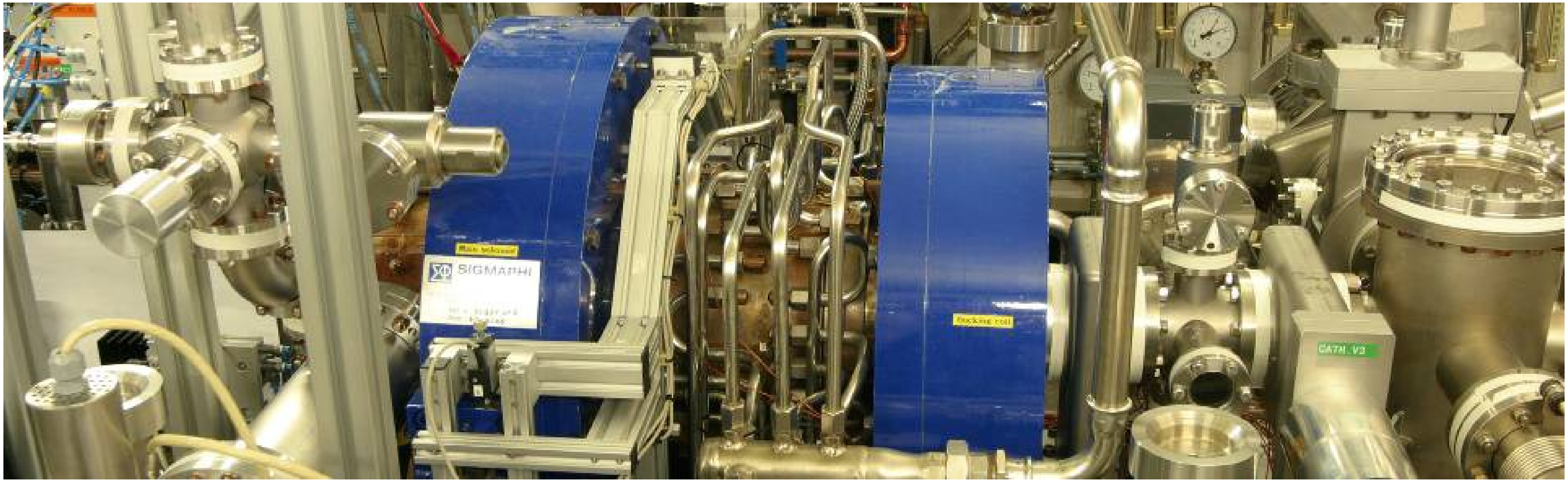
RF gun operation at PITZ.

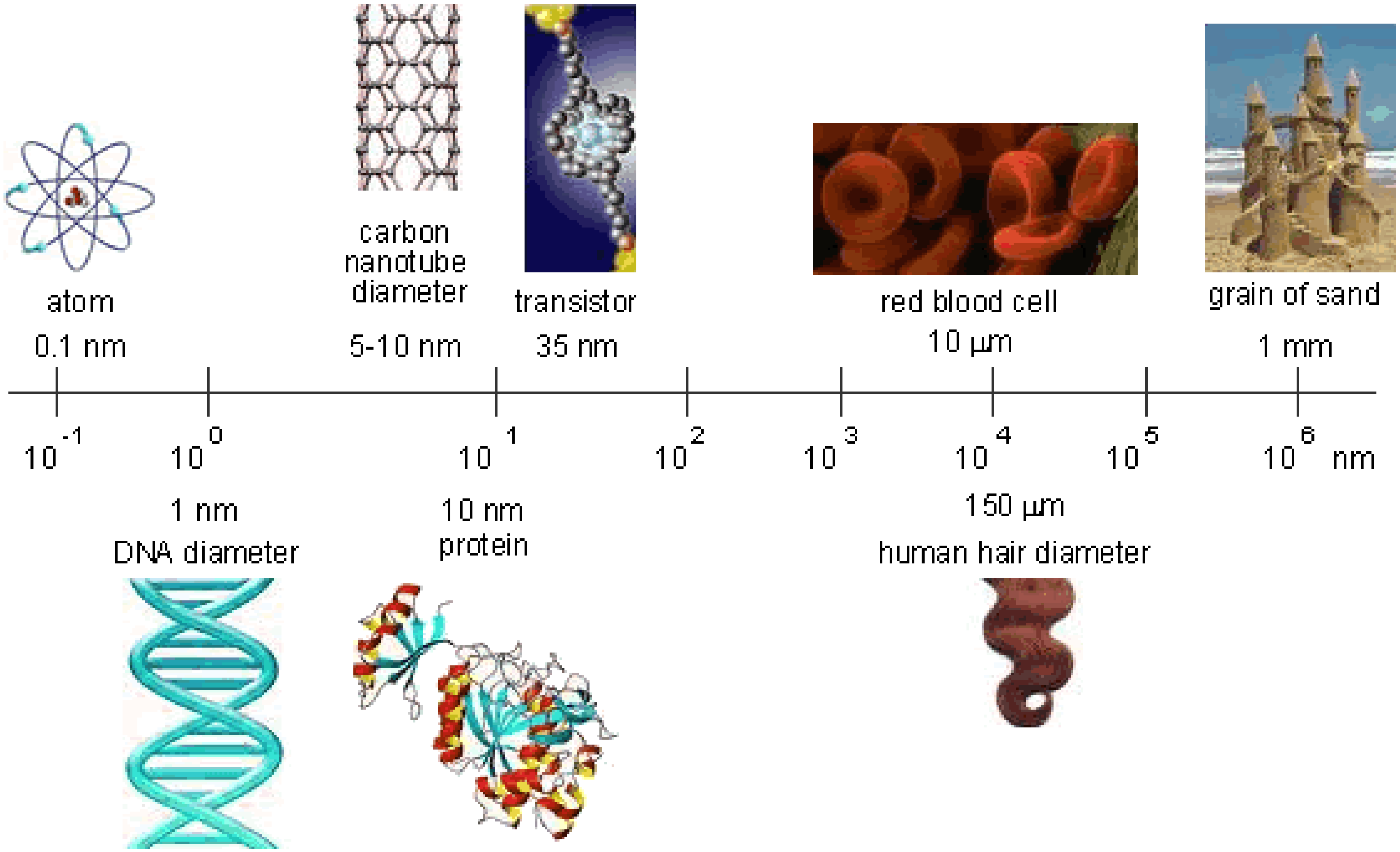


Igor Isaev
Research Seminar
Zeuthen, 05.12.2014

HELMHOLTZ
GEMEINSCHAFT

DESY

Length scales



Motivation – Free Electron Lasers

The 4th generation of synchrotron radiation sources should provide:

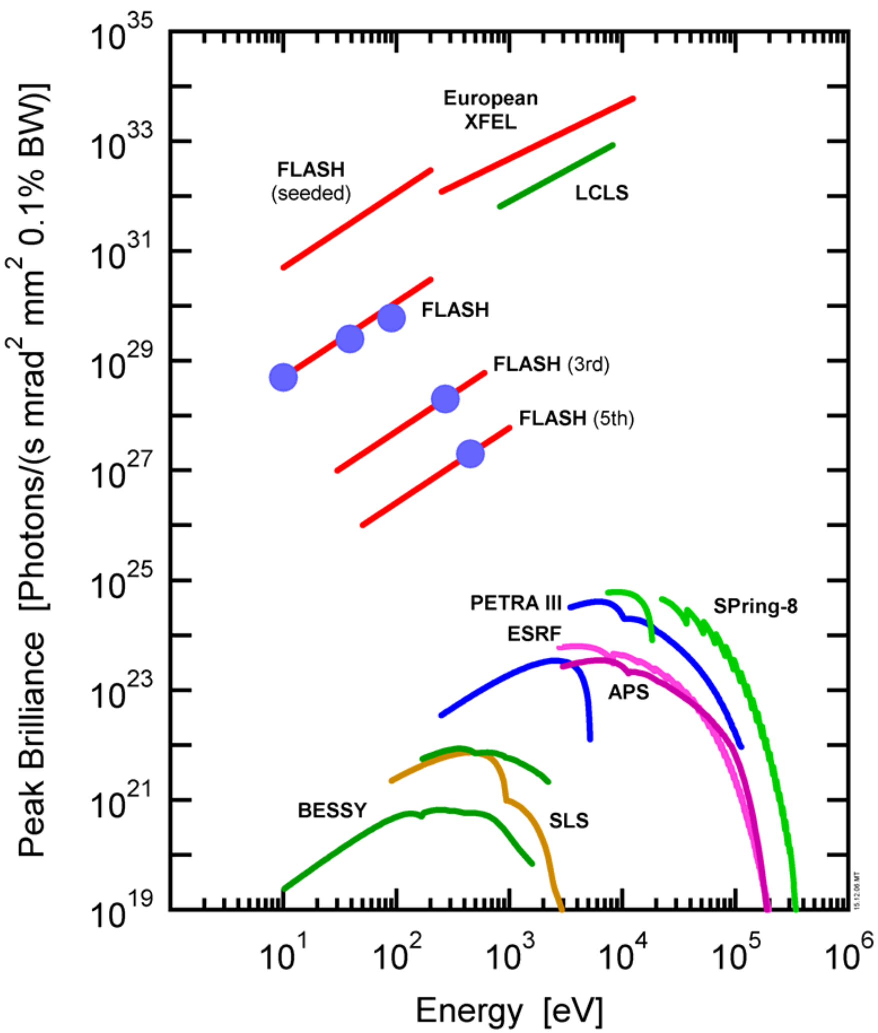
Properties of the SR radiation:

- Wavelength down to 0.1nm (Å)
- Short pulses ≤ 100fs
- Coherent light
- High peak **Brilliance**

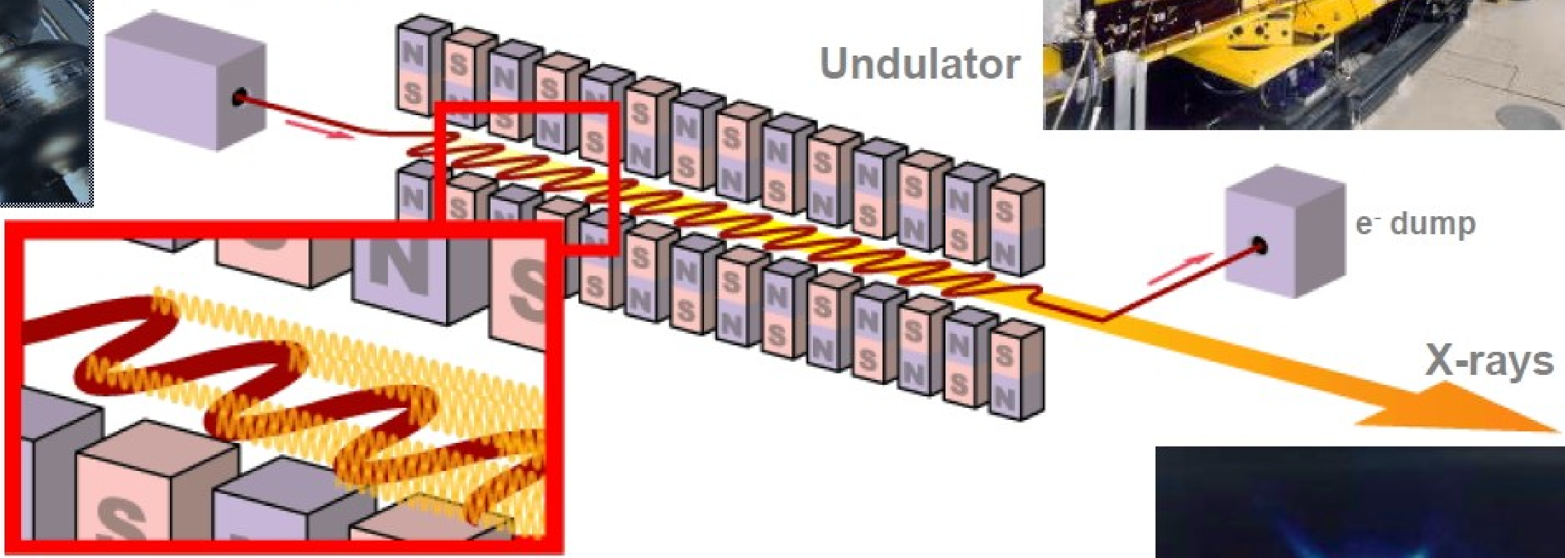
Requirements for the electrons:

High phase-space density :

- short bunch length
- small energy spread
- high bunch charge
- small area in the phase space (Emittance)



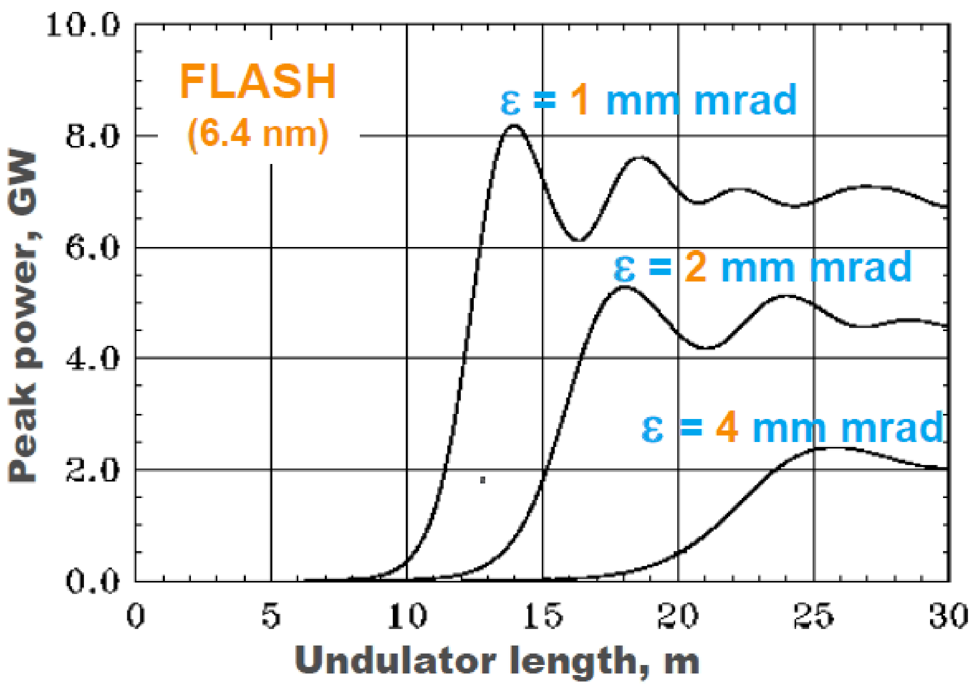
Principal layout of a (single pass) Free Electron Lasers

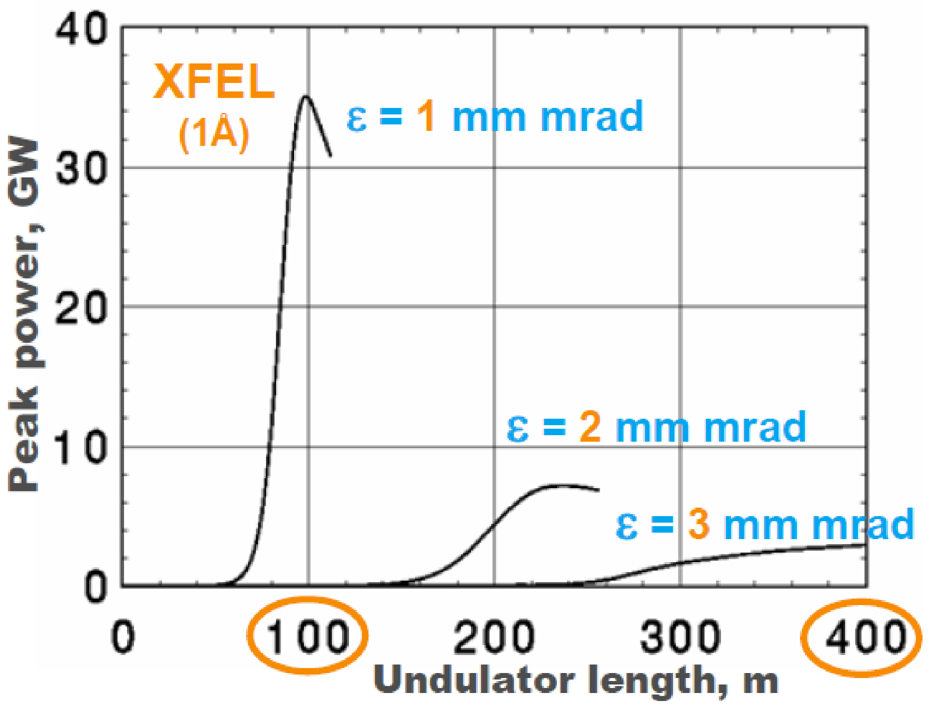


FEL radiation is similar to synchrotron radiation, but

- wavelength tunable down to 1 Å → atomic scale resolution
- ultra short pulses (fs scale) → molecular movies
- transverse spatial coherence → single nanoscale objects
- extremely high peak brilliance → matter under extreme conditions

FEL performance





- performance of an FEL depends strongly on the electron beam quality delivered by the injector, since beam quality degrades in the accelerator
- electron source must provide very small emittance electron beam

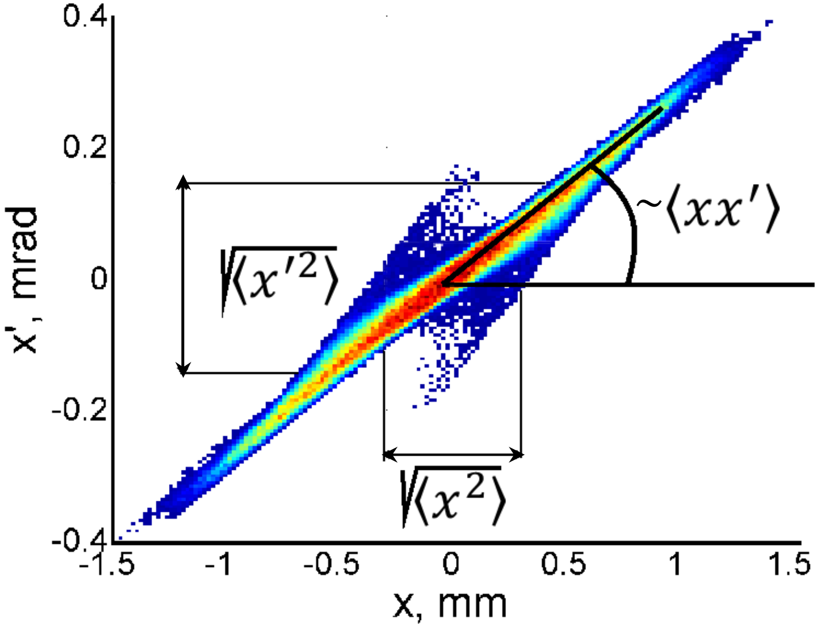
$$\lambda_{\min}[\mathrm{nm}] \approx \frac{4\pi}{10} \frac{\varepsilon_n[\mathrm{mm\ mrad}]}{\sqrt{I_p[\mathrm{kA}] \cdot L_u[\mathrm{m}]}}$$

Phase space and emittance

- The phase space of the system is the space in which all possible states of the system are represented.
- Emittance is related to the volume/area occupied by the electron beam in phase space.
- 6D phase space can be split into 3x2D phase spaces: $(x, x'); (y, y'); (z, p_z)$
- Normalized transverse rms emittance for X plane:

$$\varepsilon_{n,x} = \beta\gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

$$\beta = \frac{v}{c}, \gamma = \frac{1}{\sqrt{1-\beta^2}}$$



- Normalized transverse rms emittance for both planes:

$$\varepsilon_{n,xy} = \sqrt{\varepsilon_{n,x}\,\varepsilon_{n,y}}$$

Free Electron Lasers

- *Lower emittance* ->
  - **-> Higher SR intensity**
  - **-> Shorter undulator** (saving €)
- ***The space charge forces are by far the dominant "destroyer" of the emittance***
- **The beam quality degrades as the beam propagates downstream**

High quality electron source is must for FEL

Photo-Injector Test Facility goals

> Develop an electron source for the European XFEL:

$\Rightarrow$ very small transverse emittance (<1 mm mrad @ 1 nC)

$\Rightarrow$ stable production of short bunches with small energy spread

> Extensive R&D on photo-injectors in parallel to FLASH operation

> Compare detailed experimental results with simulations:

$\Rightarrow$ benchmark theoretical understanding of photo-injectors

> Prepare and characterize RF guns for subsequent operation at FLASH / XFEL

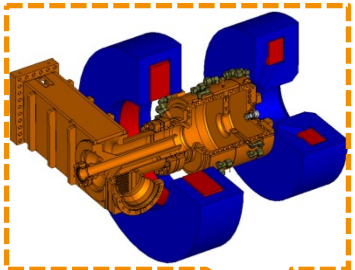
> Test new developments (laser, cathodes, beam diagnostics)

PITZ facility

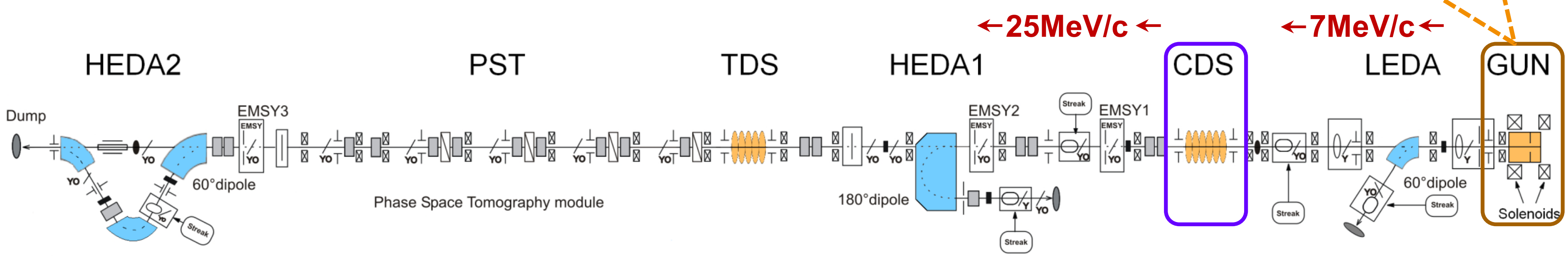
- RF photoelectron gun
- Booster
- Diagnostics:
  - slit scan (transverse phase space)
  - streak camera, TDS, dipole (longitudinal phase space)
  - screen stations (beam shape)
  - tomography (transverse phase space)

Facility parameters

Parameter	Value
Beam bunch charge, nC	0.001 .. **4**
Beam momentum after gun / booster, MeV/c	**7 / 25**
Number of pulses in a train	≤800
Repetition rate, Hz	10
Maximum average beam current, µA	≤32
Optimized emittance (1nC), mm mrad	<0.9



- New developments (e.g. plasma acceleration)

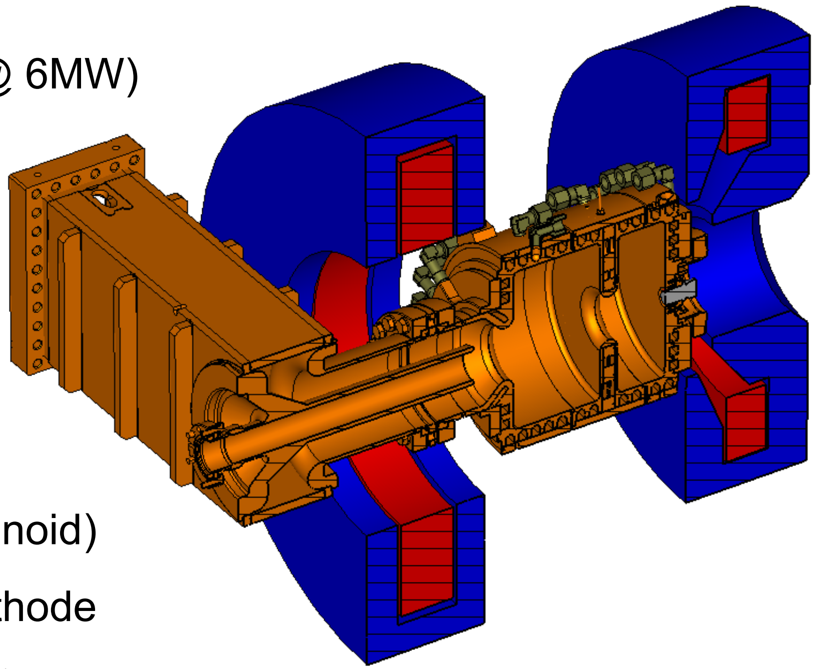


Photoelectron gun setup

PITZ photoelectron gun setup consists of:

> RF cavity

- L-band 1.6-cell copper (OFHC) cavity
- Dry-ice cleaning → low dark current (<100 μA @ 6MW)
- Cs_2Te photocathode (QE ~5-10 %) with load-lock system
- LLRF control for amplitude and phase stability



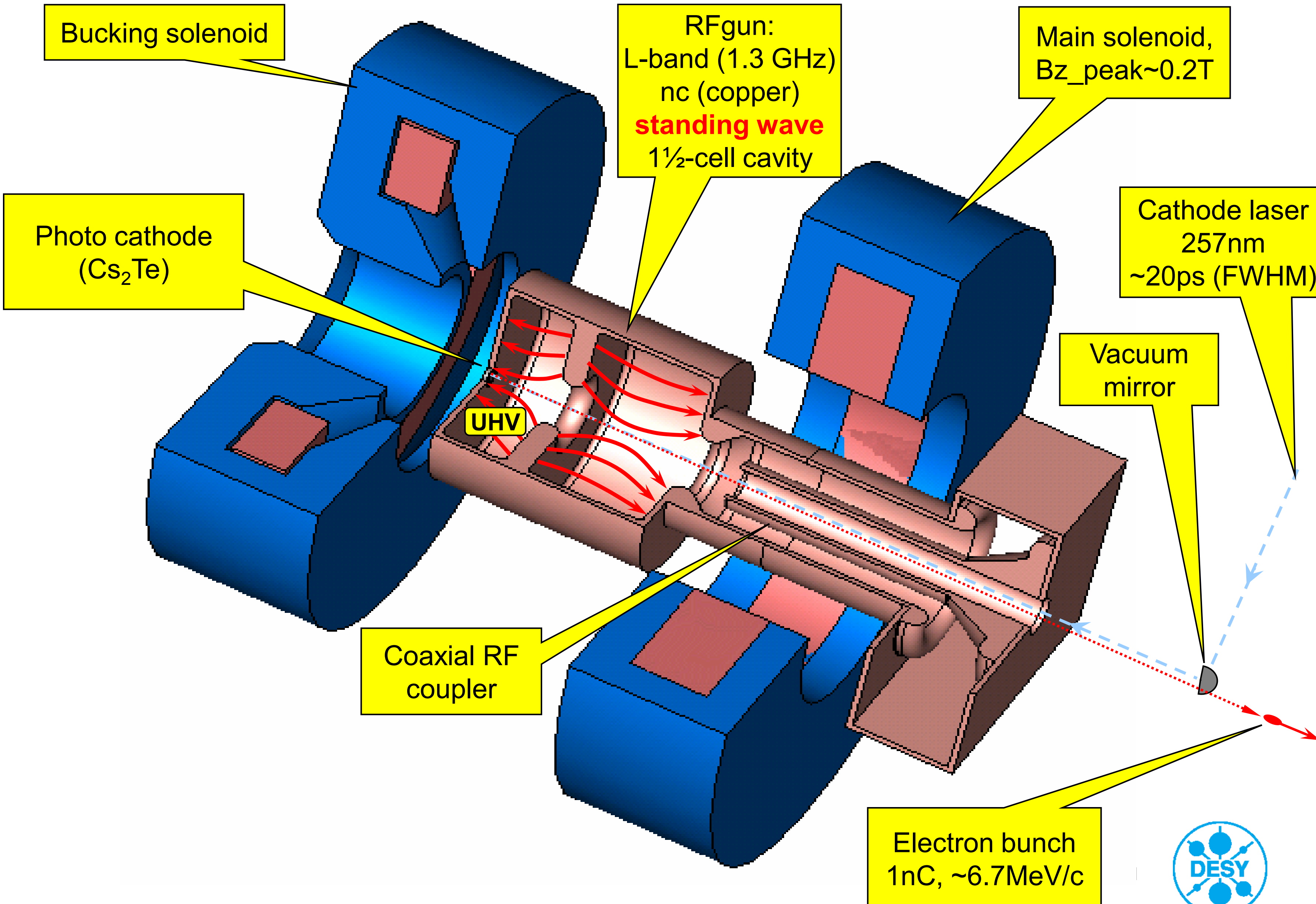
> Solenoids

- Dedicated for emittance compensation
- Max. on-axis field ~0.3 T (500 A in the main solenoid)
- Bucking solenoid for compensation of field at cathode

> Photocathode laser

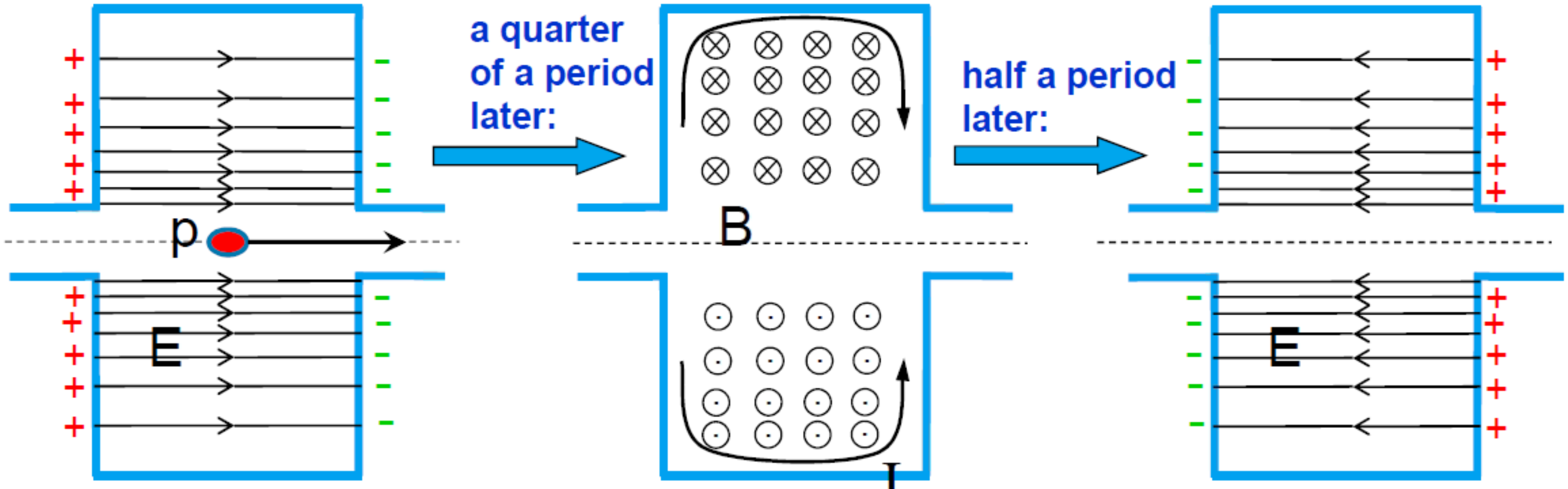
- Pulse train structure
- Micropulses temporally and spatially shaped

PITZ RF-Gun

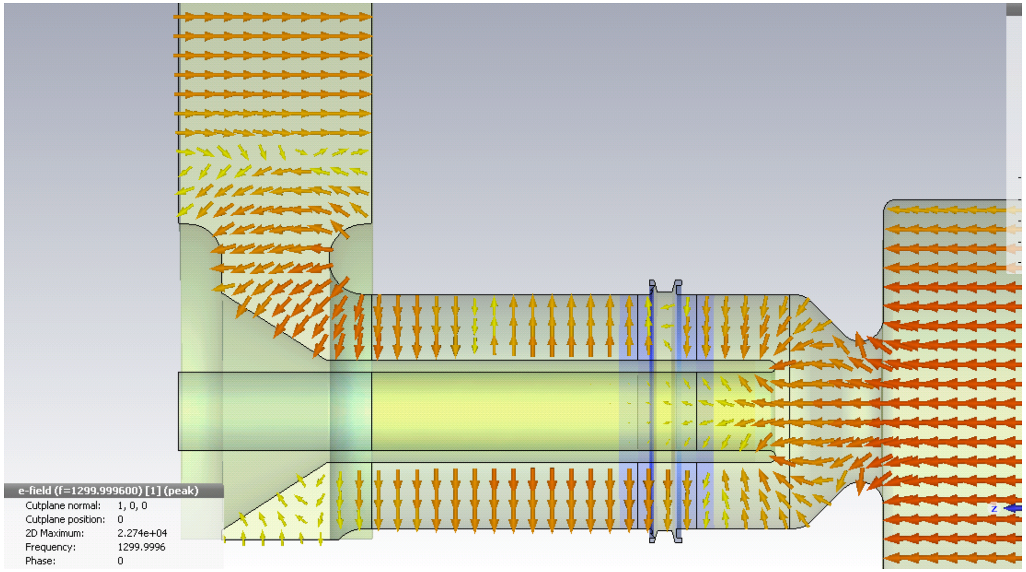


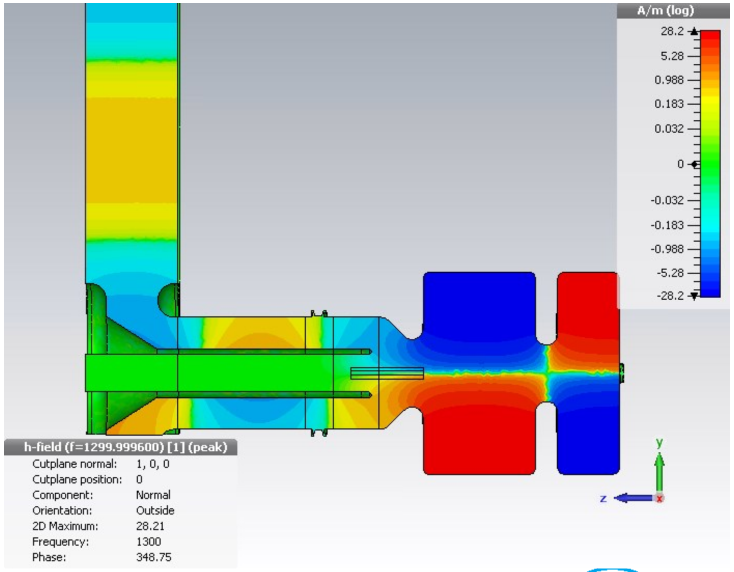
Bucking solenoid
RFgun:
L-band (1.3 GHz)
nc (copper)
standing wave
1½-cell cavity
Main solenoid,
Bz_peak~0.2T
Photo cathode
(Cs_2Te)
Cathode laser
257nm
~20ps (FWHM)
Vacuum
mirror
UHV
Coaxial RF
coupler
Electron bunch
1nC, ~6.7MeV/c

RF field gun



RF field distribution





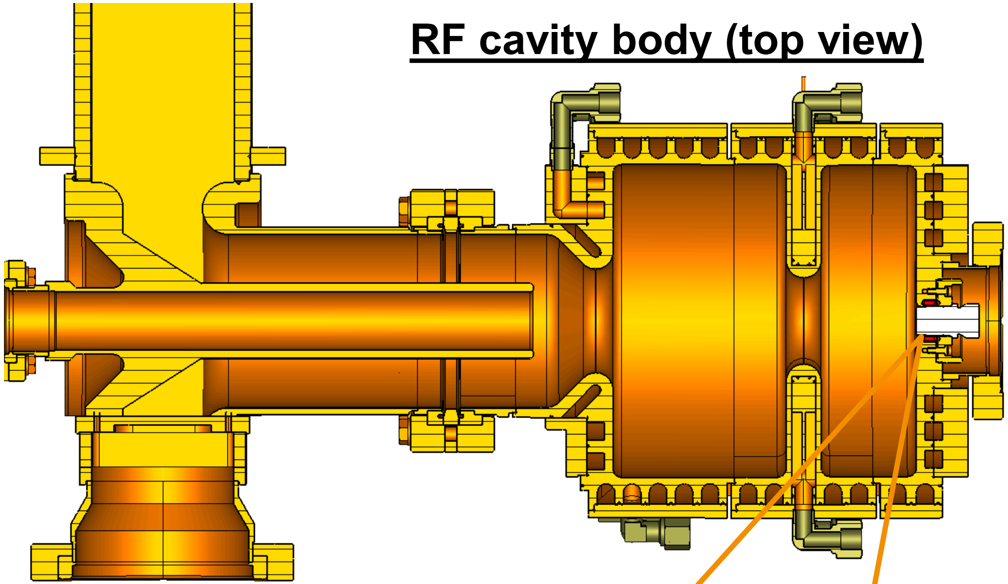
RF cavity

The RF photo gun cavity operates with a standing wave regime in the π-mode with resonant frequency of 1.3 GHz

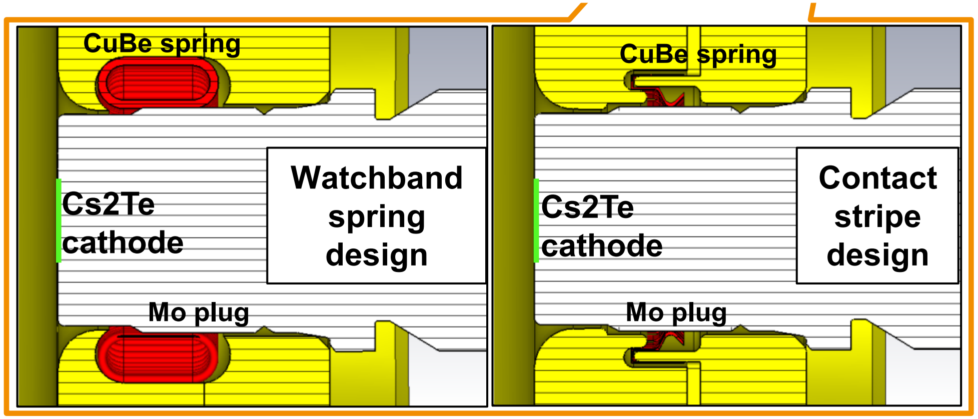
Main parameters

Parameter	Value
Max. accelerating gradient at the cathode, MV/m	**60**
Frequency, MHz	**1300**
Unloaded quality factor	~20000
Beam momentum after gun, MeV/c	7
RF peak power, MW	**6.5**
RF pulse duration, μs	**≤650**
Repetition rate, Hz	10

RF cavity body (top view)



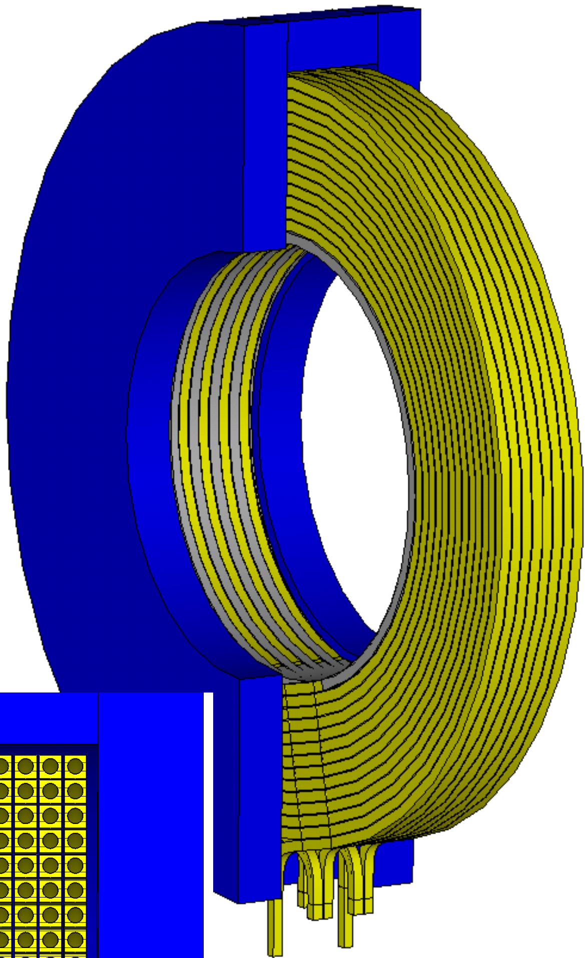
Two designs of the cathode area

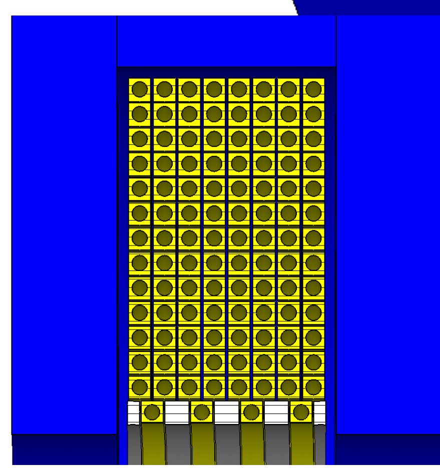


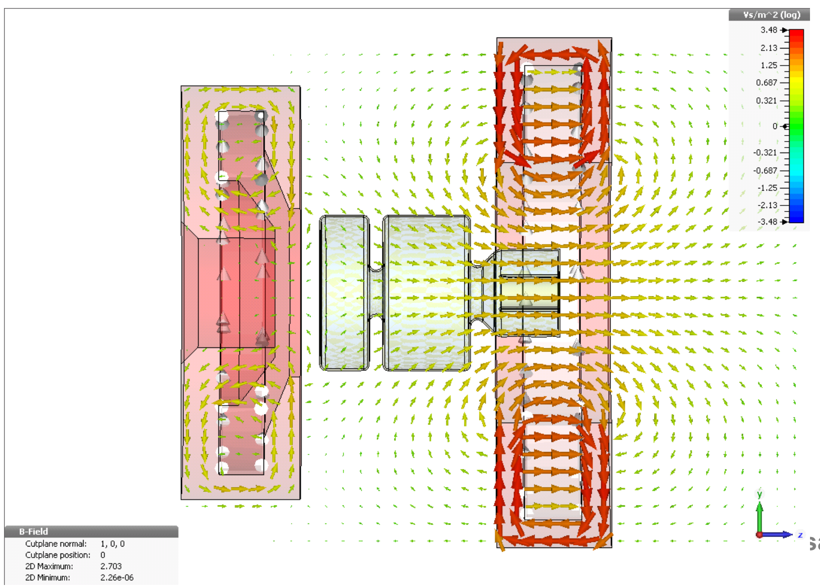
Solenoids

The cavity is surrounded by a main solenoid and a bucking solenoid for focusing purposes and in order to compensate space charge forces.

Parameter	Main solenoid	Bucking solenoid
Wire material	Copper	
Shield material	Iron	
Inductivity, T	0.28	0.15
Max current, A	500	300
Number of turns	108	57

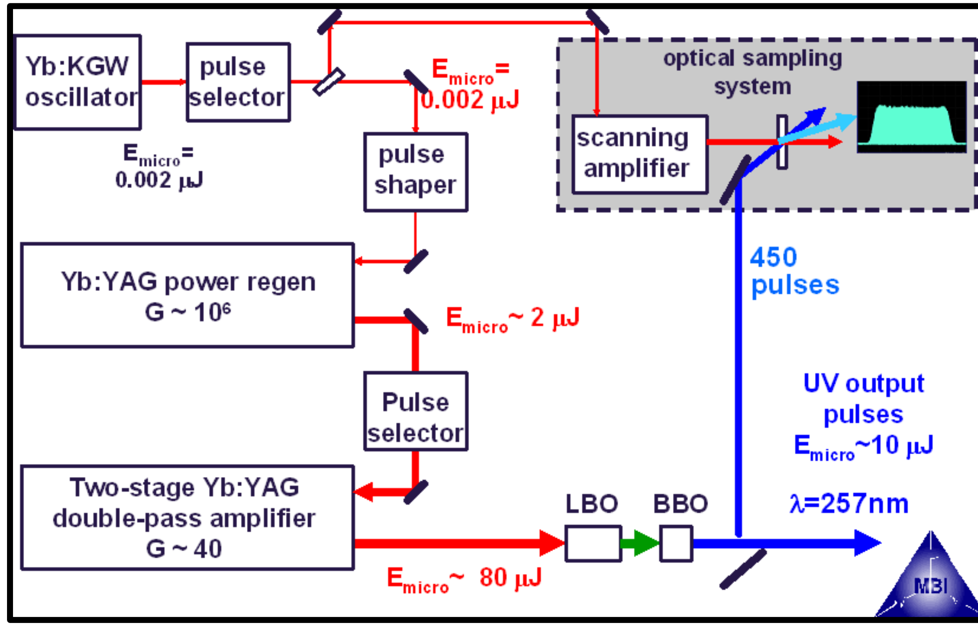




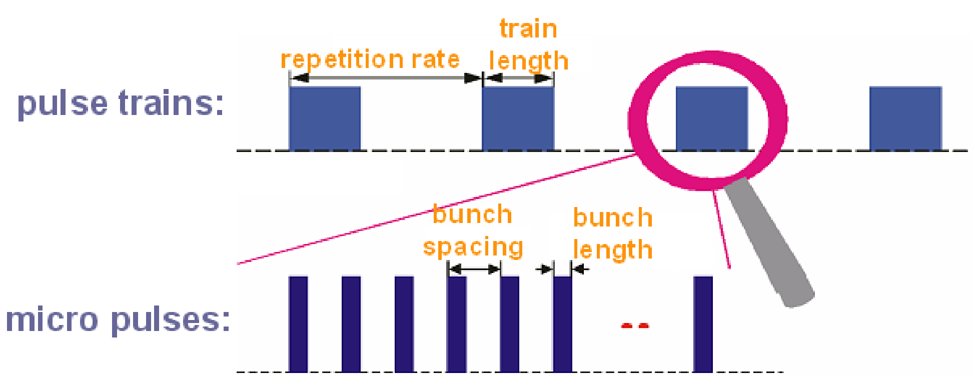


Photocathode laser system (developed by MBI)

- Ytterbium-doped YAG laser (Yb:YAG)
- UV output pulses (4th harmonic)
  - λ = 257 nm
  - repetition rate = 1 MHz
  - up to 800 micro pulses/train
  - max. micro pulse energy: ~10 μJ
- Characterization of longitudinal laser (micro)pulse shape using Optical Sampling System (OSS)



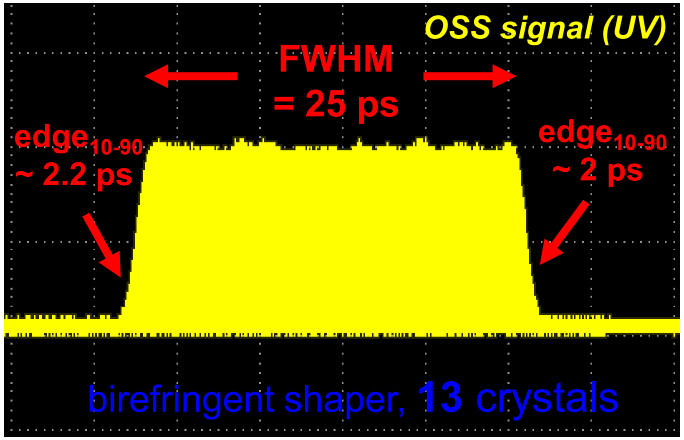
Time structure for FLASH and European XFEL ⇒ demonstration at PITZ

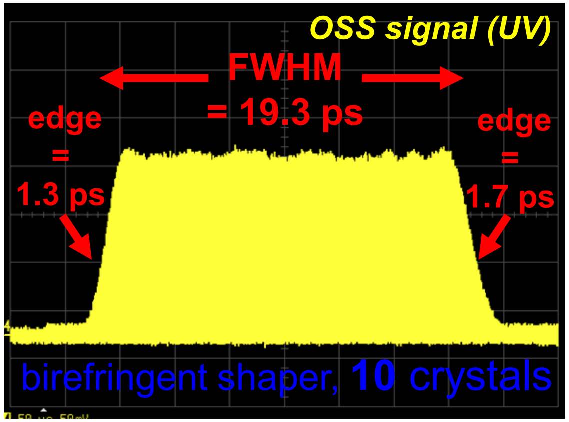


Parameters	FLASH	European XFEL
max. RF repetition rate	10 Hz	10 Hz
max. train length	800 μs	650 μs
bunch spacing	1 μs	0.2 – 1 μs

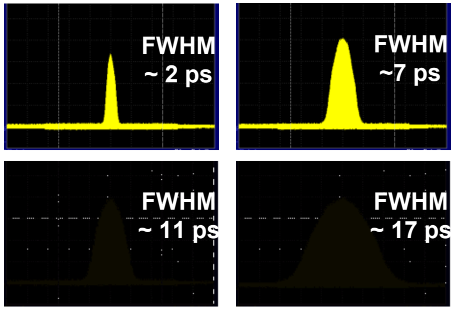
Photocathode Laser: *Temporal Pulse Shaping*

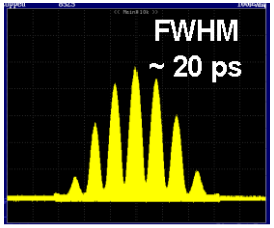
UV pulses of different shapes can be produced at the PITZ photo cathode



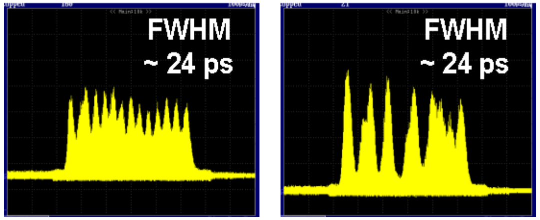


Gaussian:





Simulated pulse-stacker

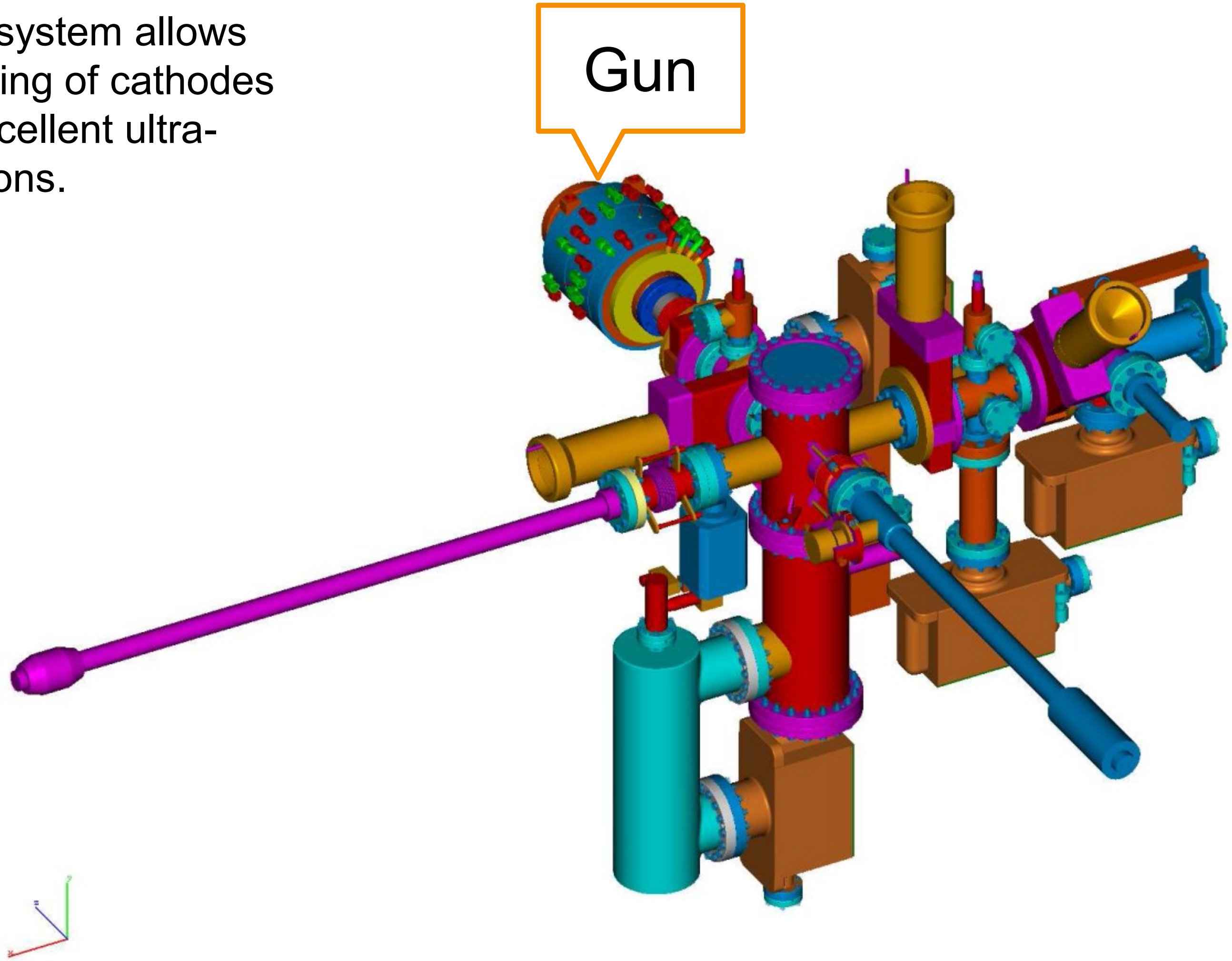


→ High flexibility of photo cathode laser system

Photocathode load-lock system

- A load lock cathode system allows mounting and changing of cathodes while maintaining excellent ultra-high vacuum conditions.

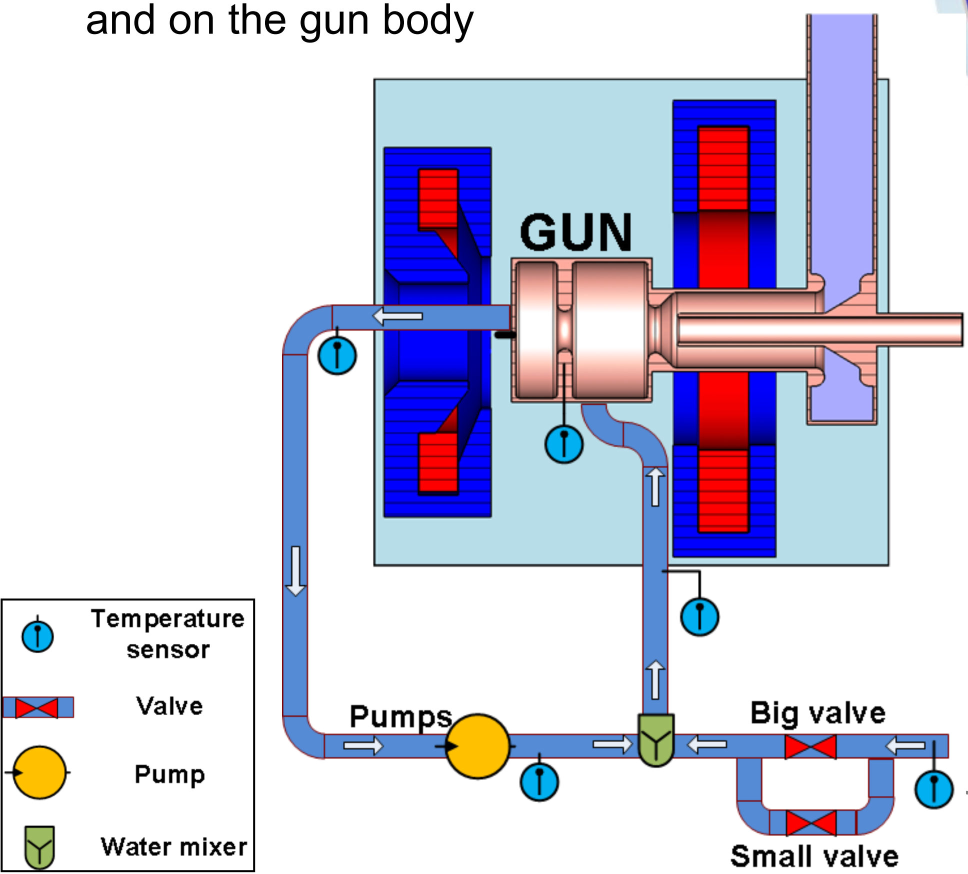
Cathode plug



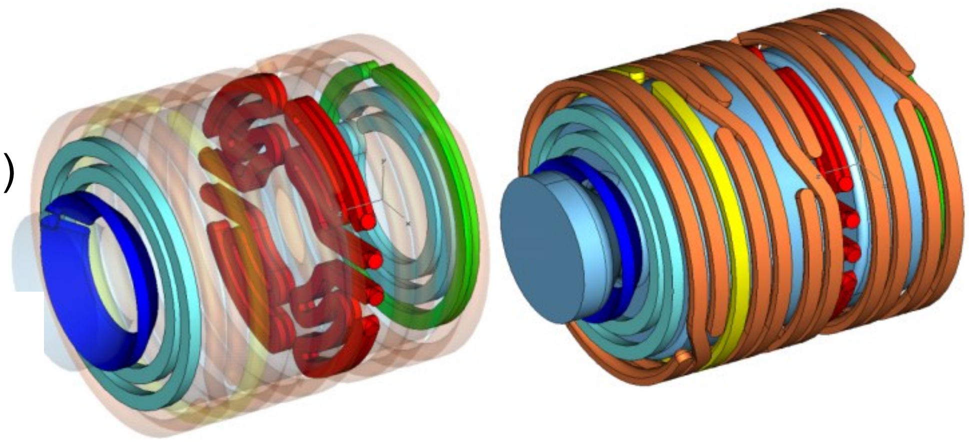
Water cooling system

Water cooling system consists of:

- Circle with warm water
- Big (slow) and small (fast) valves for controlling of cool water
- Pump stations (doubled due to safety issues)
- Temperature sensors along the water pipes and on the gun body



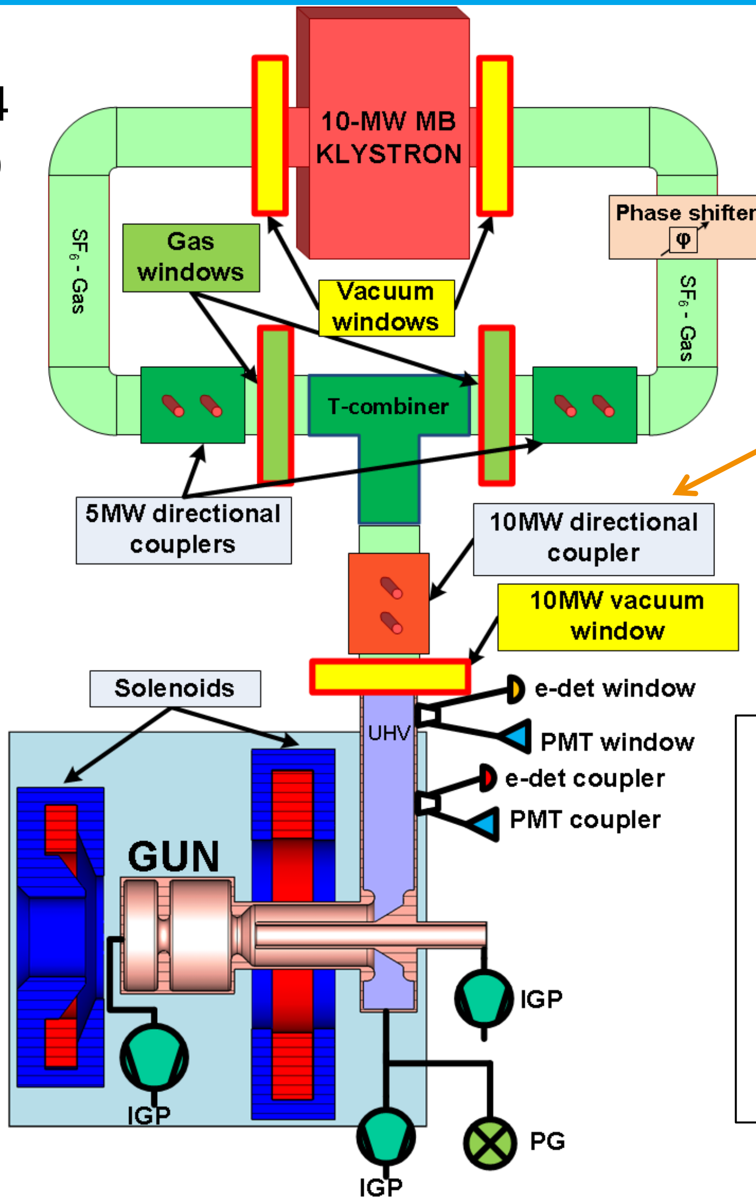
RF cavity water cooling channels
(Gun 4 prototype)



- 14 cooling cooling channels are surrounding gun body
- Input water goes to 2 reservoirs which serve the water cooling channels
- Water temperature, flow, speed and pressure detectors are installed at each of 14 output channels

RF system layout for a gun

Setup used in the period November 2012 – May 2014 (Gun 3.1, Gun 4.3, Gun 4.4)



RF regulation by FB loop is possible due to 10 MW directional coupler

PMT - Photomultiplier tube

e-det – Electron detector

IGP – Ion getter pump (pressure reading)

PG - Pressure gauge

Interlock (IL) system of PITZ

- The PITZ gun IL system is designed to protect the accelerator from damage. It quickly stops the LLRF.
- The PITZ IL system **reaction time is in the range of a few microseconds → RF can be stopped within the RF pulse**
- IL system collects signals from all IL devices and produces a common IL signal which stops the RF power.

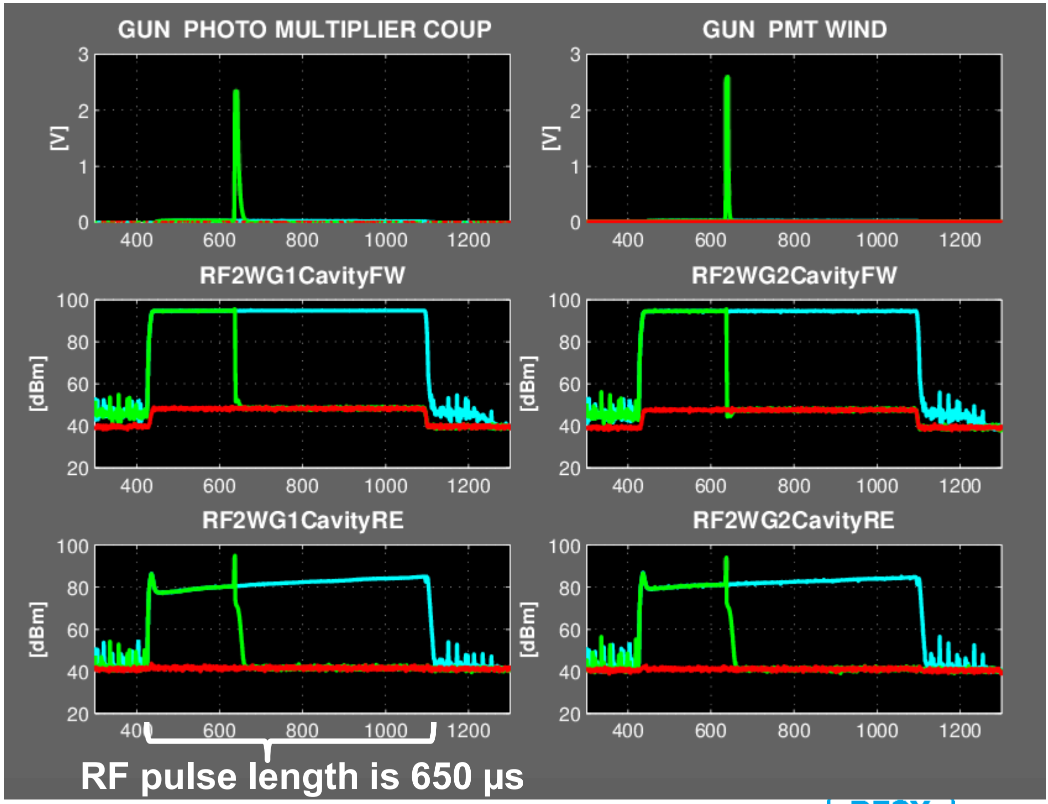
Undisturbed RF pulse →

→ IL event detected →

→ RF pulse interrupted →

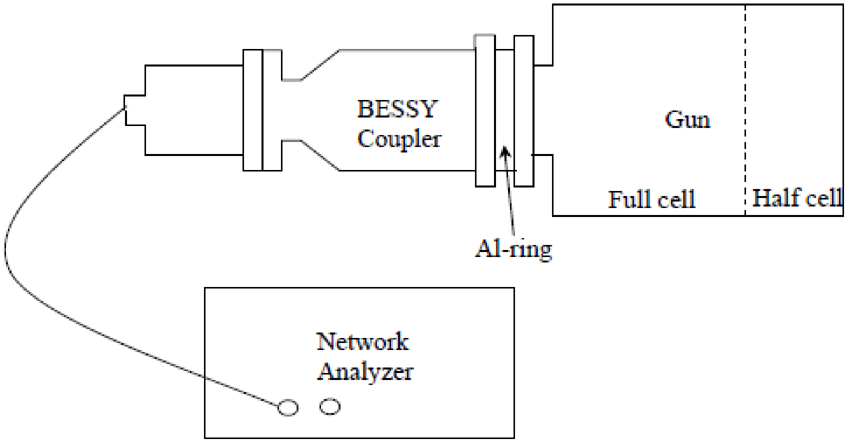
→ Signals after IL event

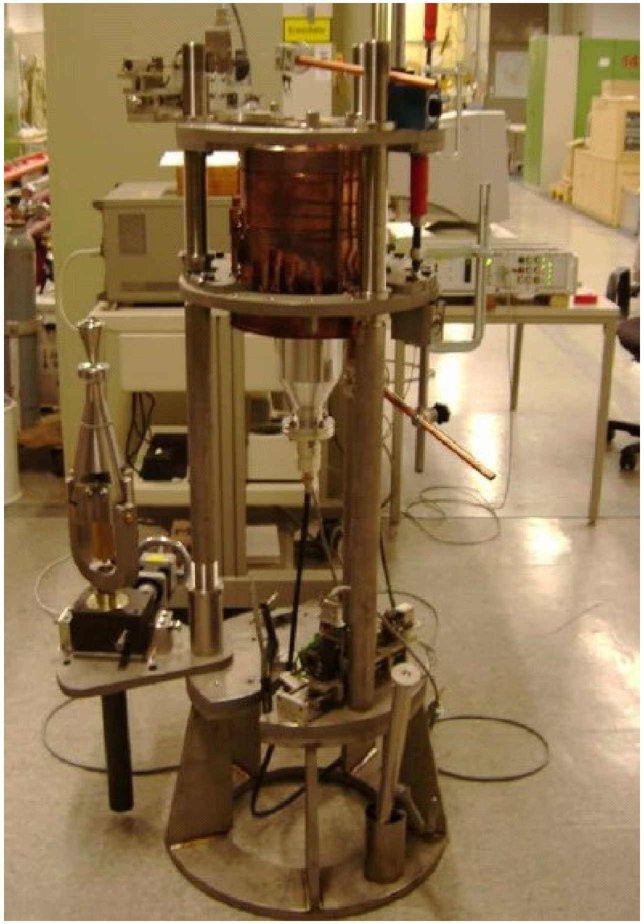
(RF is off)



Gun tuning

Measurement Setup





Measurements:

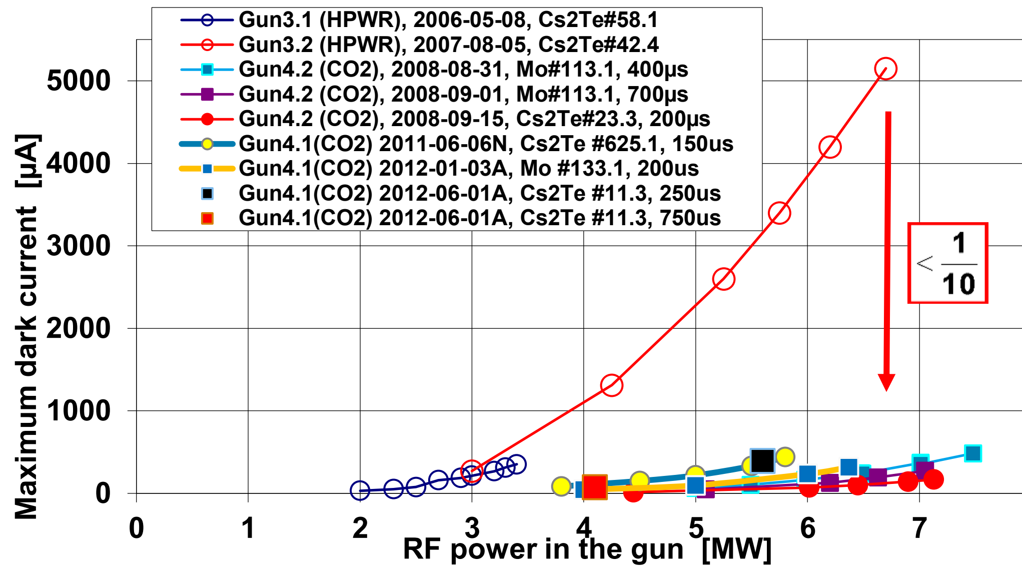
- Frequency tuning
- Measure π-mode and 0-mode frequencies using S11
- Measure Q-values for π-mode and 0-mode
- Bead-pull Measurements

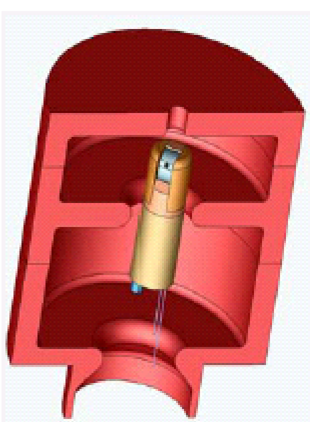
Gun dark current measurements

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

Vertical cleaning setup with 110° rotating nozzle.

Dark current in Faraday cup versus RF power for different Guns and cathodes





Gun 4.2: dry-ice sublimation-impulse cleaning
(previous guns: high-pressure water rinsing) -> significant DC reduction by **factor of 10**
(DC comes mainly from cathode not gun cavity)

Conditioning procedure for a gun

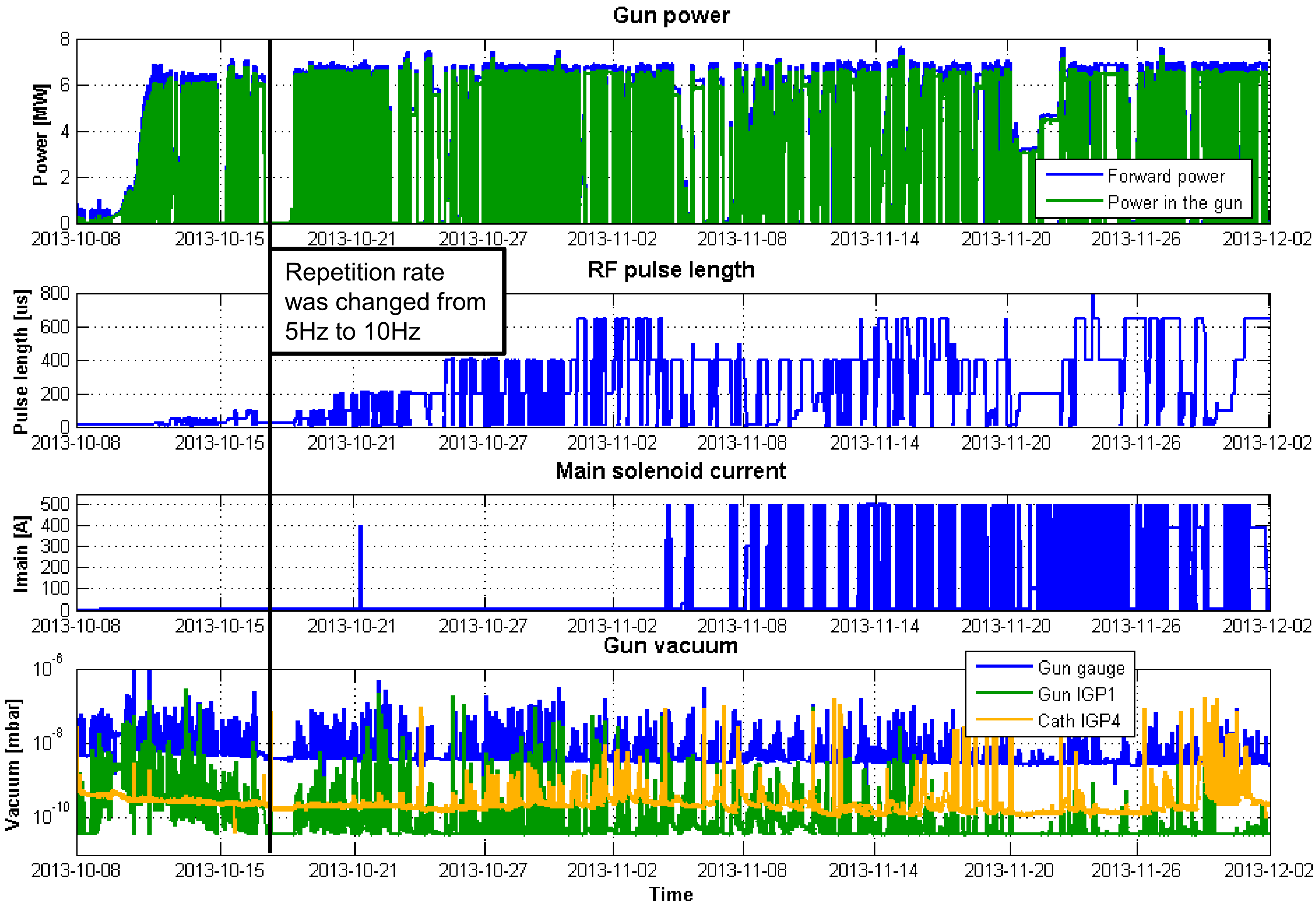
Step	Rep. Rate, Hz	RF pulse length, µs	RF power range, MW
1	5	10	0 .. Max
2	5	20	0 .. Max
3	5	50	0 .. Max
4	5	100	0 .. Max
5	10	10	0 .. Max
6	10	50	0 .. Max
7	10	100	0 .. Max
8	10	200	0 .. Max
9	10	400	0 .. Max
10	10	650	0 .. Max

*** Max power for the Gun 4.3 and Gun 4.4 is 6.5 MW**

Ramp-up procedure(defined by THALES):

- RF power increase by steps of max 0.2 MW every 15 min. for new RF pulse length (to be noted that circulator transparency gets higher at high average power)
- vacuum pressure < 10^{-7} mbar (Thales requirement)
- In case of significant vacuum or other trips:
  - re-ramp RF power from 0 with short pulses (10 µs)
  - restart with step 1 or step 5 respectively
  - increase the pulse length in reasonable steps
- Initially, the rf gun solenoid is off (then sweep)
- No feedback

Beginning of Gun 4.4 run history (from 08.10.2013 until 02.12.2013)



Beam diagnostics

> Bunch charge
  - Faraday Cup (FC)
  - Integrating Current Transformer (ICT)

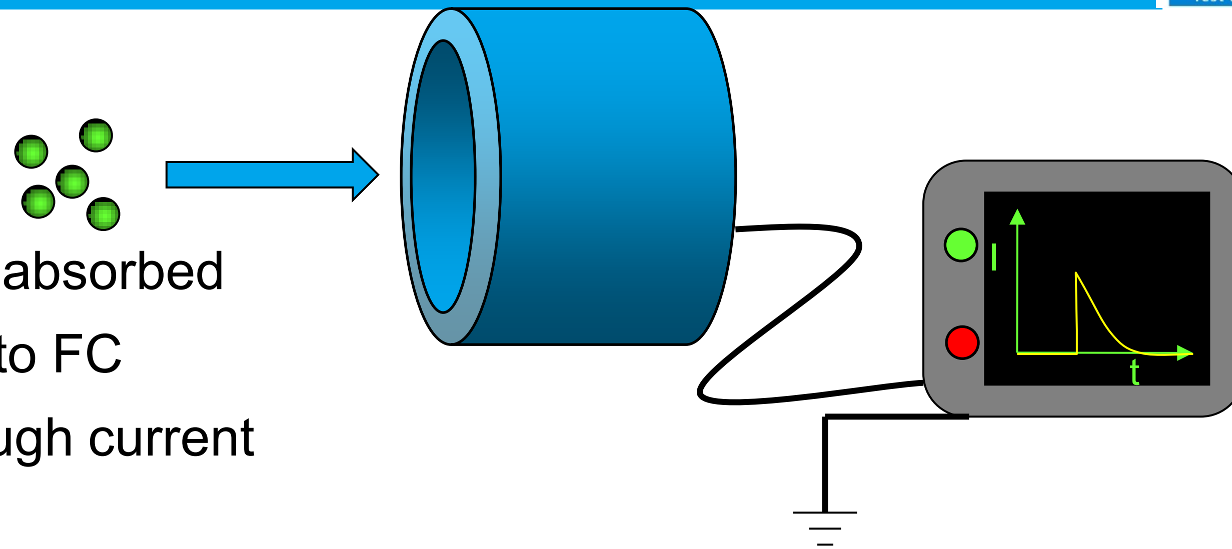
> Beam size, shape and position
  - view screen (YAG, OTR)
  - beam position monitor

> Beam momentum and momentum spread
  - dipole magnets

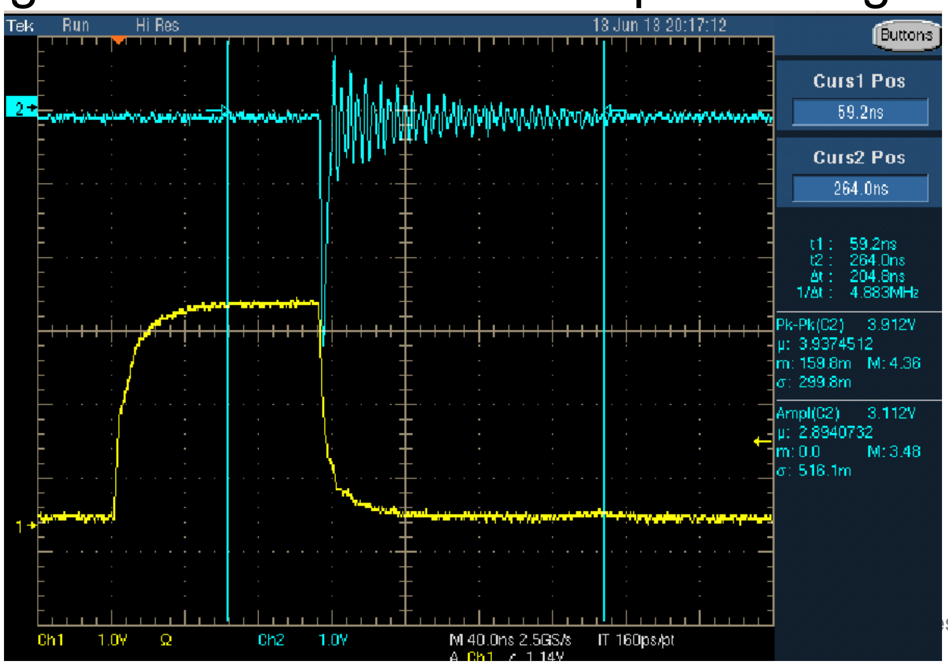
> Bunch length, longitudinal phase space
  - aerogel + streak camera
  - RF deflecting cavity
  - dipole magnets

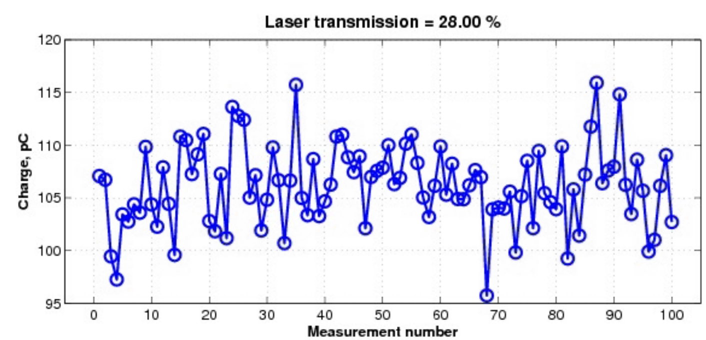
> Transverse emittance and phase space
  - screens and slit masks
  - phase-space tomography

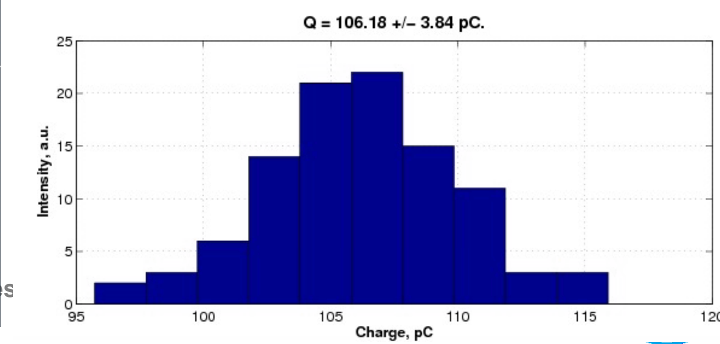
Bunch charge measurements. Faraday Cup.



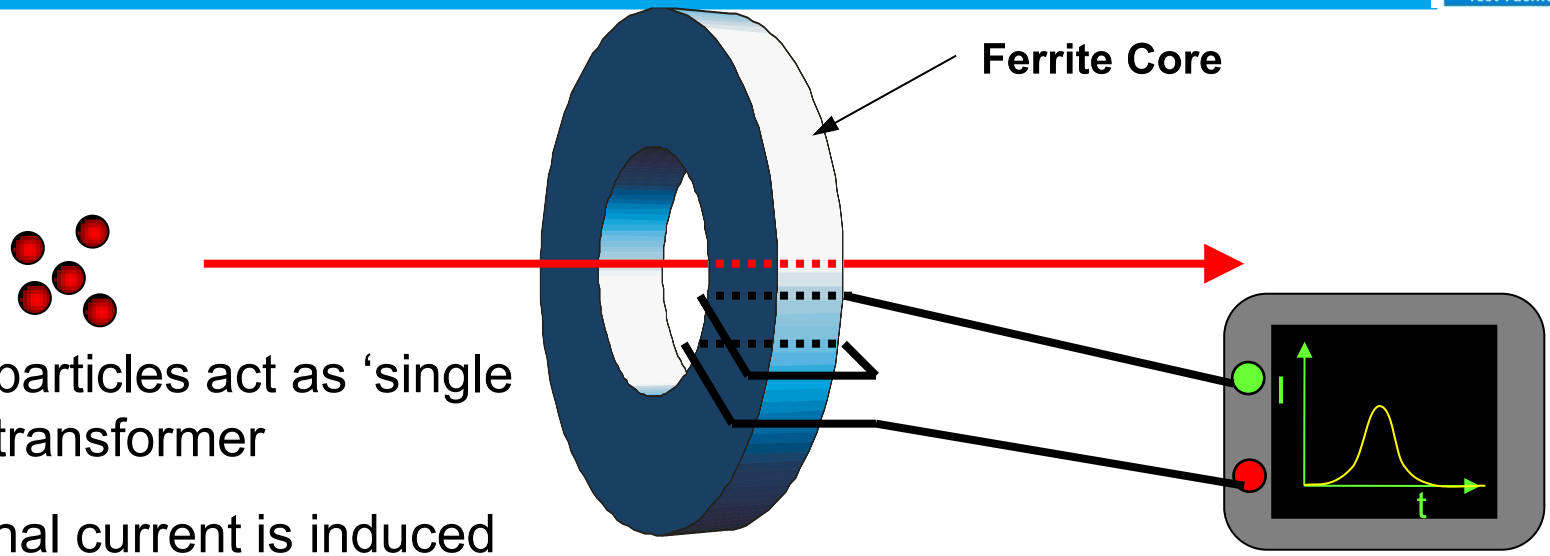
- Charged particles are absorbed
- Charge is transferred to FC
- FC is discharged through current measurement
- Integral of current over time equals charge



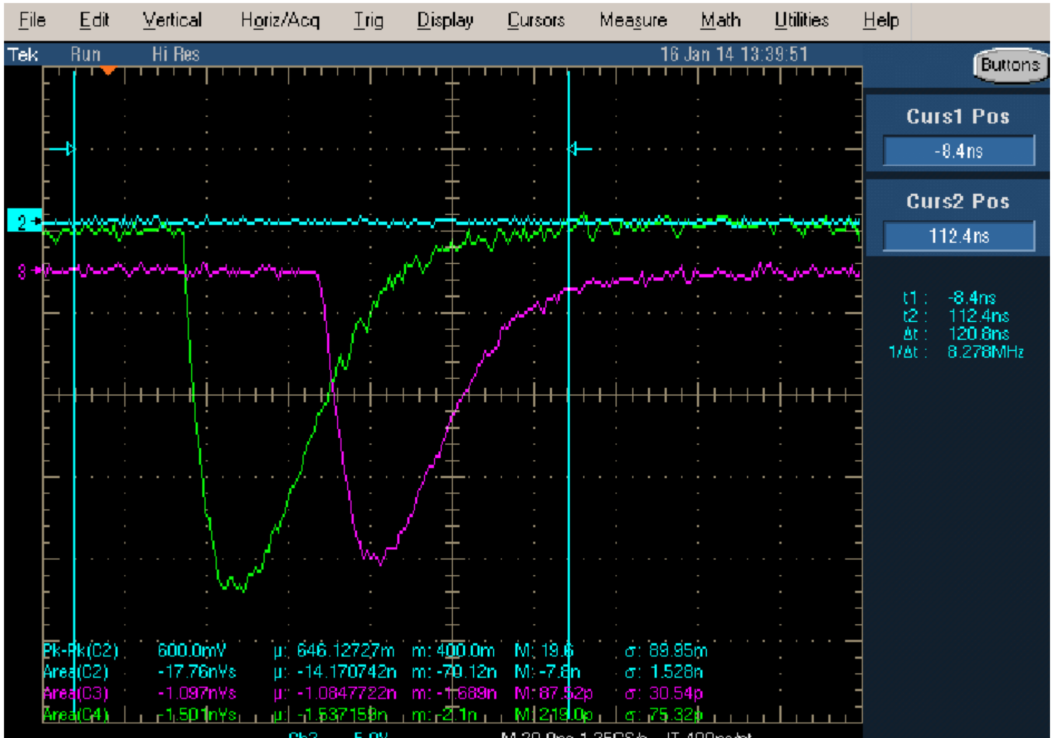




Bunch charge measurements. ICT.

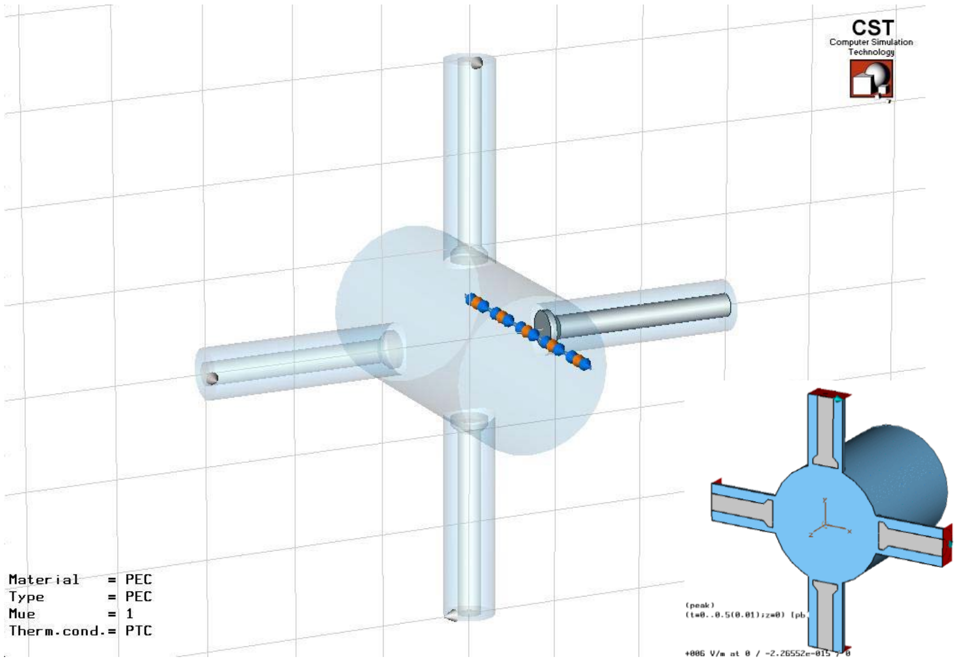


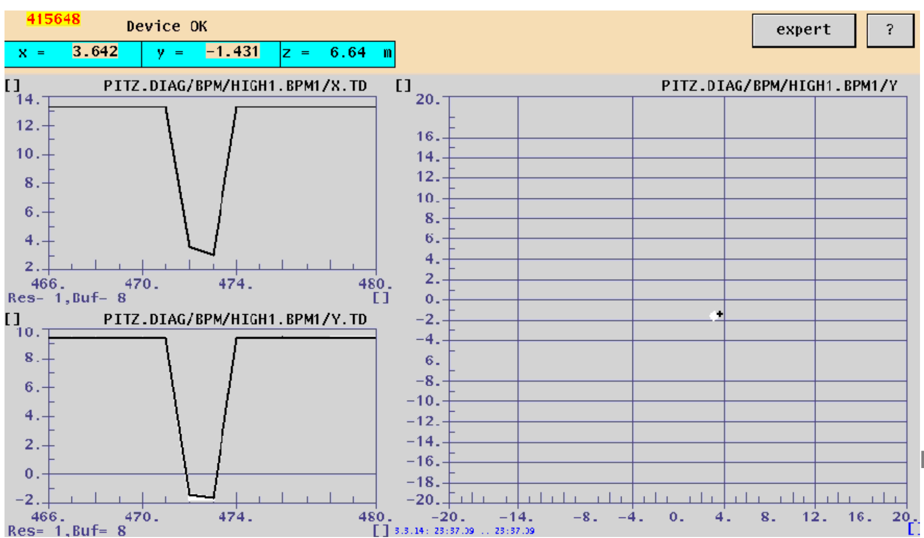
- Charged particles act as 'single turn' in a transformer
- Proportional current is induced into windings
- Integral of current over time equals charge



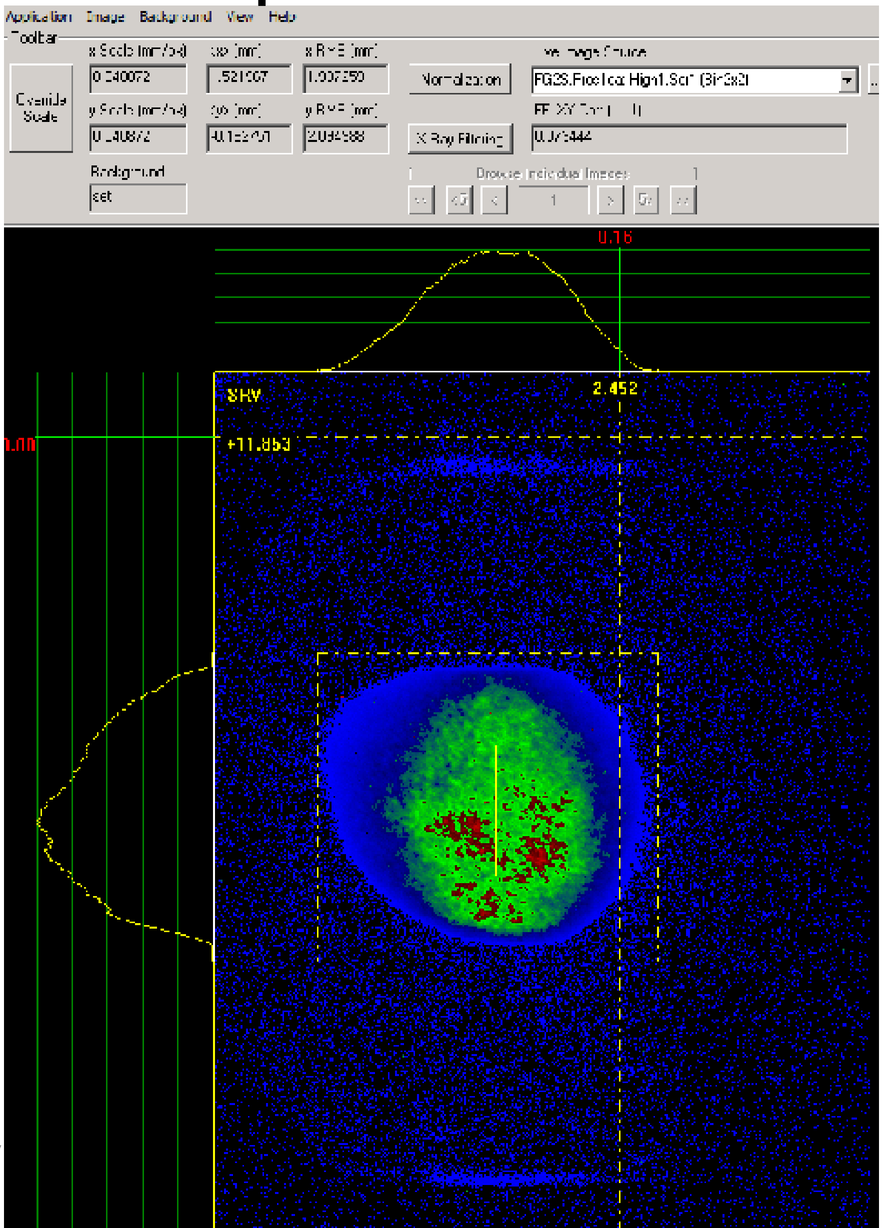
Beam size, shape and position

Beam position monitor



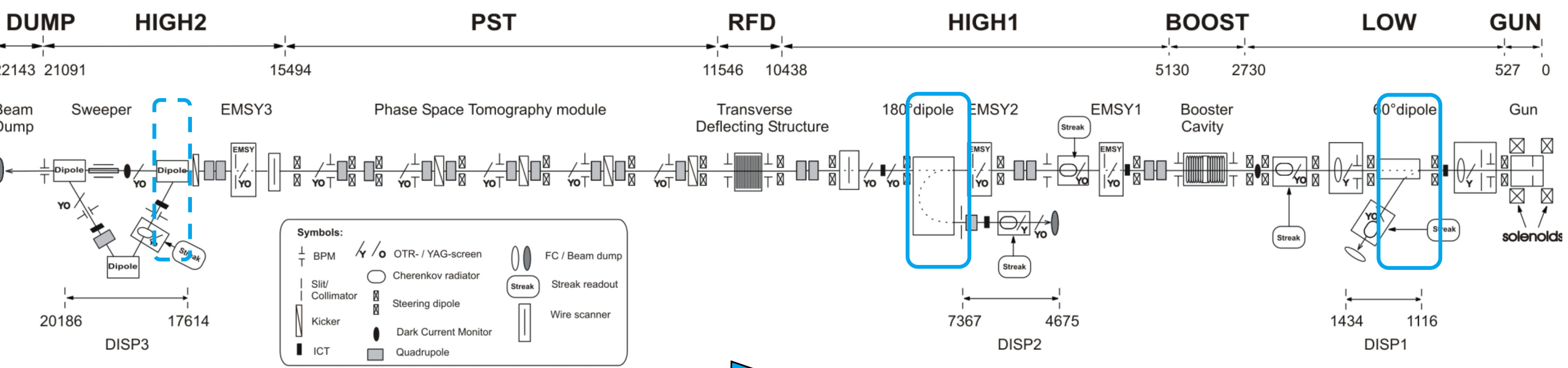


Beam picture at the screen

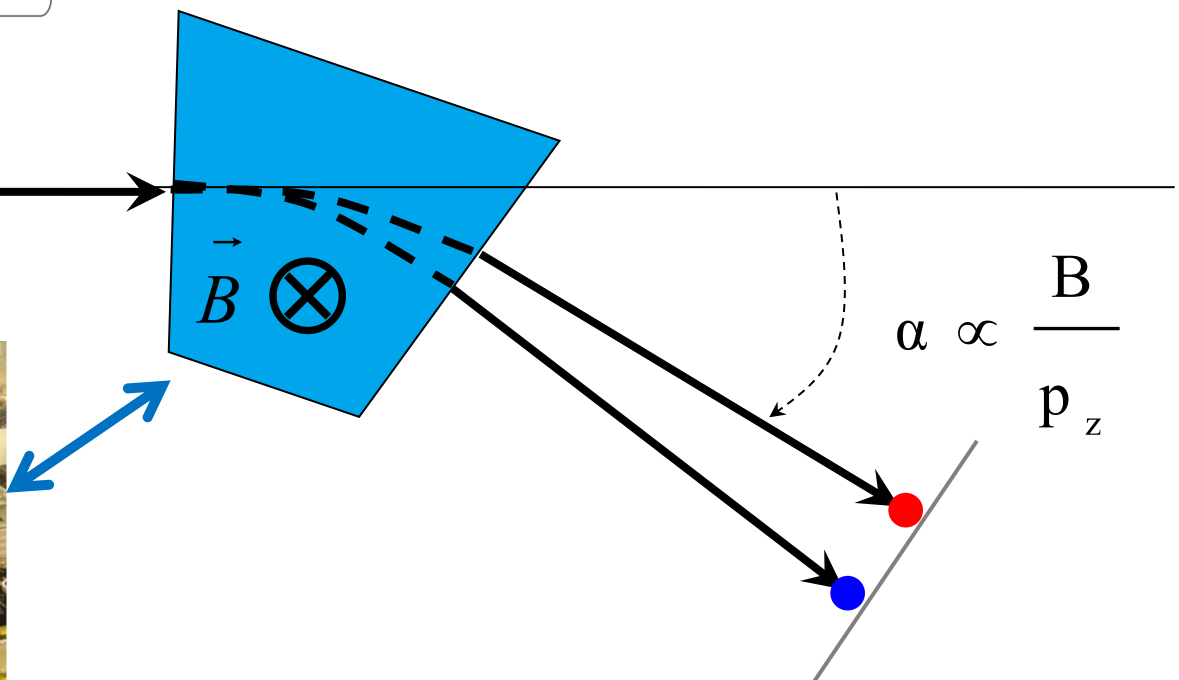


Isaev

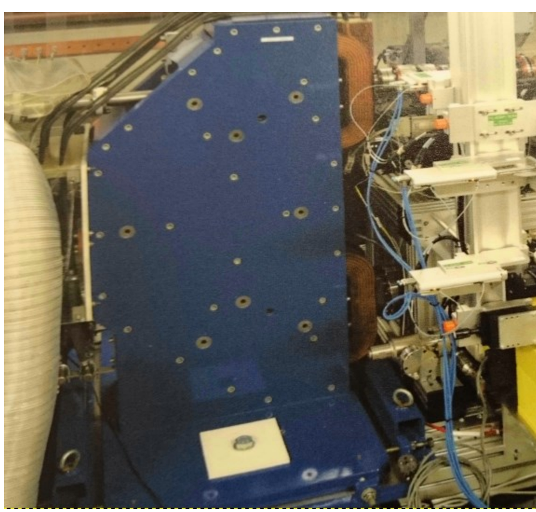
Momentum and momentum spread measurements



Using spectrometer dipoles



$$\alpha \propto \frac{B}{p_z}$$



Observation screen

Beam momentum and momentum spread

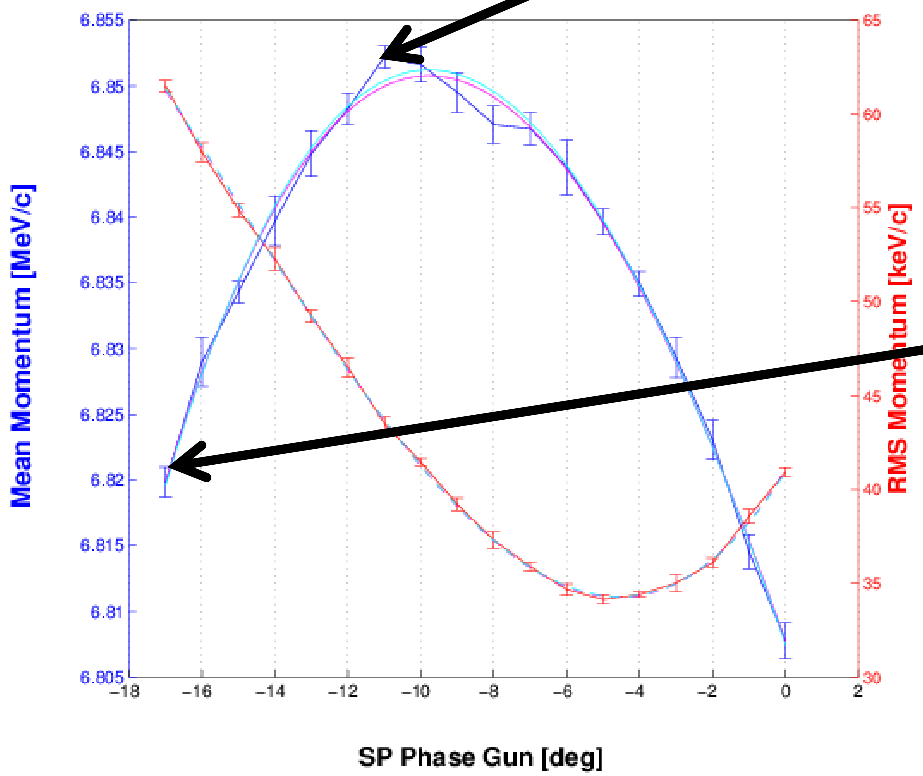
Momentum scan

Measured at: LEDA

$\langle p \rangle_{max}$ = (6.8522 ± 0.0008)MeV/c at –11°

p^{RMS}_{min} = (34.1 ± 0.2)keV/c at –5°

Imain = 452.0A
Idip = –1.8407A
Stats: Img(Bkg): 10(10)
6 pulses
LT = 60%
SP–Plgrs = 51.0
Power = 6.34MW
Reflection = 36%%



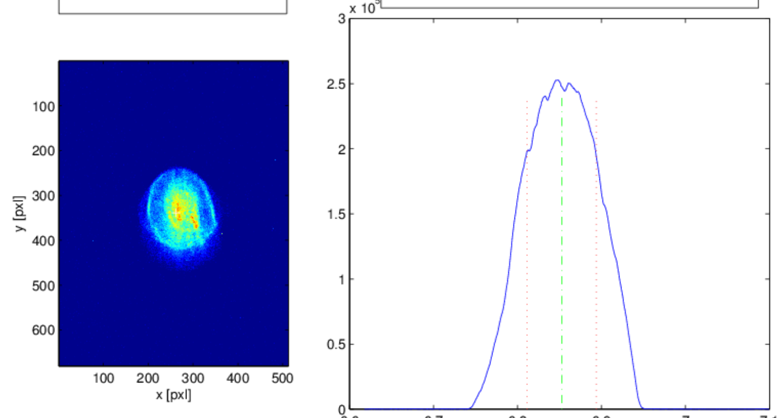
Momentum projections

Phase: –11°

Statistics (Img): 30
Statistics (Bkg): 10

p_{mean} = (6.8525 ± 0.0010)MeV/c

p_{RMS} = (41.3 ± 0.5)keV/c

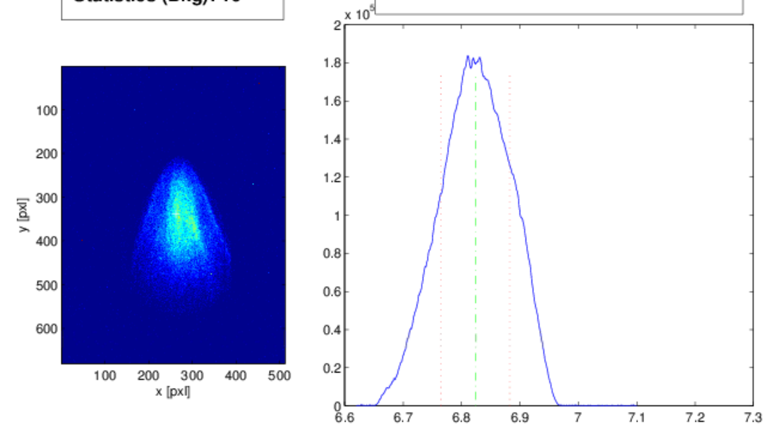


Phase: –17°

Statistics (Img): 30
Statistics (Bkg): 10

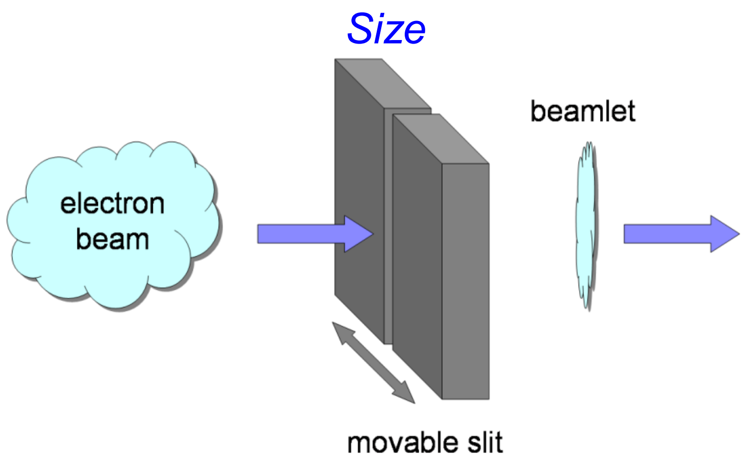
p_{mean} = (6.8236 ± 0.0012)MeV/c

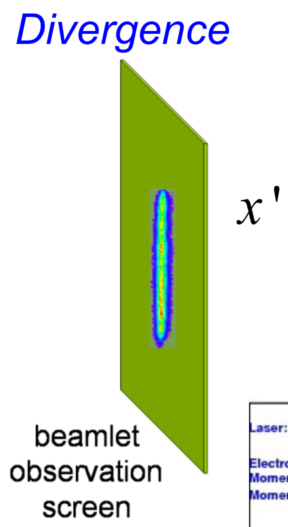
p_{RMS} = (59.0 ± 0.6)keV/c

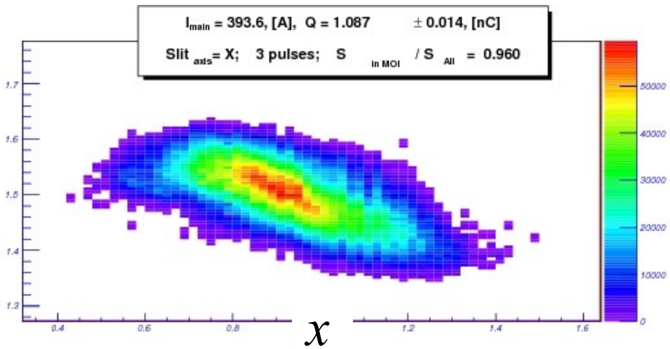


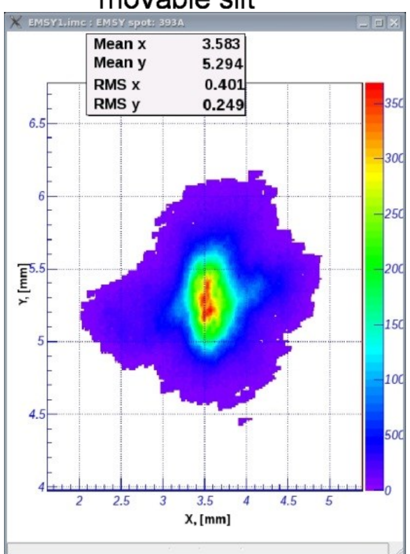
Transverse emittance measurements. Slit scan.

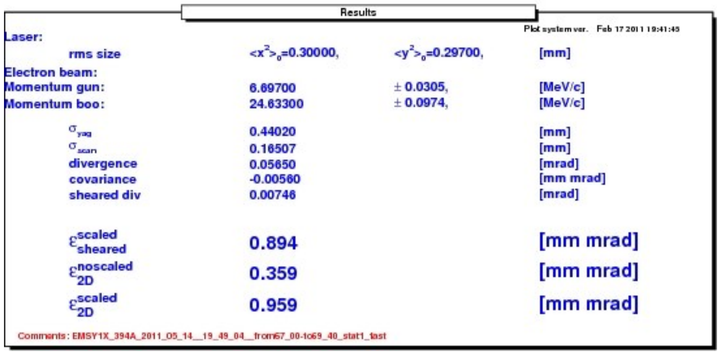
> Idea: When space charge forces are too strong -> cut out small pieces of the actual beam and measure the divergence of these “beamlets”









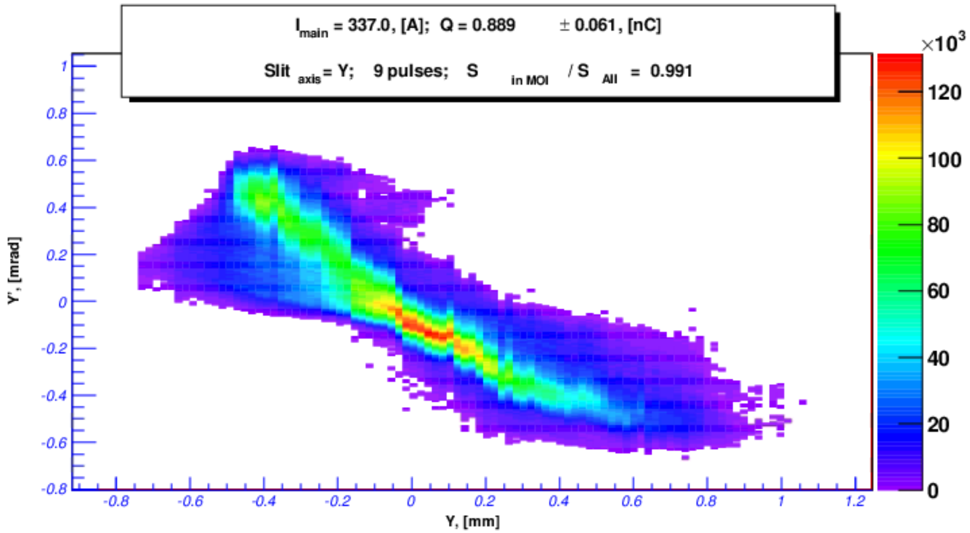

Results

Plot system ver. Feb 17 2011 19:41:45

Laser:			
rms size	$<x^2>_0$=0.30000,	$<y^2>_0$=0.29700,	[mm]
Electron beam:			
Momentum gun:	6.69700	± 0.0305,	[MeV/c]
Momentum boo:	24.63300	± 0.0974,	[MeV/c]
σ_{yag}	0.44020		[mm]
σ_{scan}	0.16507		[mm]
divergence	0.05650		[mrad]
covariance	-0.00560		[mm mrad]
sheared div	0.00746		[mrad]
$\varepsilon^{scaled}_{sheared}$	0.894		[mm mrad]
$\varepsilon^{noscaled}_{2D}$	0.359		[mm mrad]
$\varepsilon^{scaled}_{2D}$	0.959		[mm mrad]

Comments: EMSY1X_394A_2011_05_14__19_49_04__from67_00-to69_40_stat1_fast

Transverse emittance measurements. Slit scan.



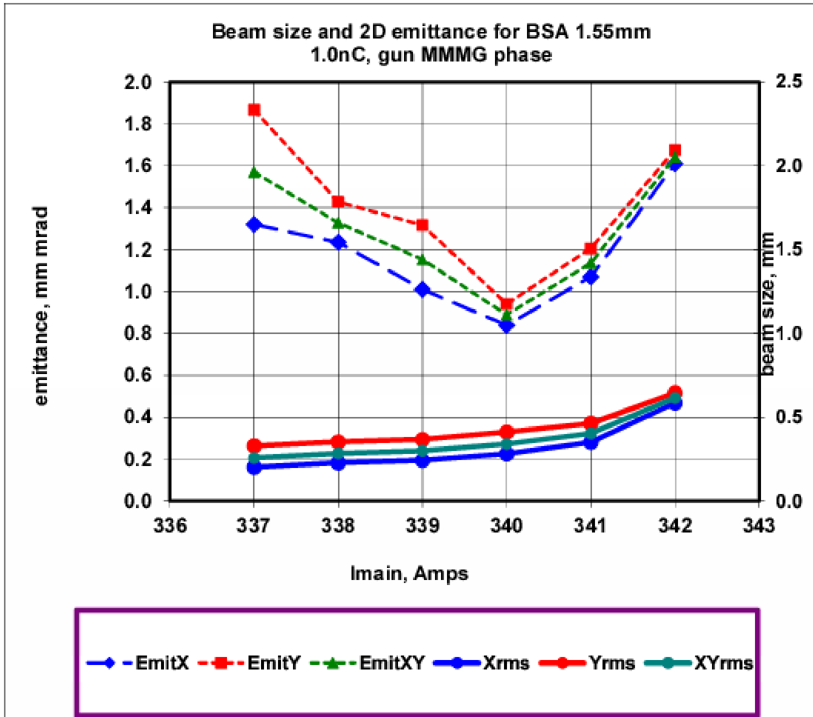
I_main (A)	Xrms, mm	Yrms, mm	EmitX_2D, mm mrad	EmitX_2D, nonscaled	XYrms, mm	EMSY1 NoP	EMSY1 Gain	MOI NoP	MOI, Gain	XBL NoP	XBL gain	EmitY_2D, mm mrad	EmitY_2D, nonscaled	YBL NoP	YBL gain	EmitXY_2D, mm.mrad	EmitXY_2D, nonscaled
Shutter speed 50 us for all BL measurements																	
337	0.202	0.329	1.320	0.842	0.258	1	10	1	10	7	20	1.868	1.873	9	21	1.57	1.256
338	0.228	0.353	1.235	0.755	0.284	1	12	1	12	5	20	1.428	1.272	5	21	1.328	0.98
339	0.243	0.368	1.010	0.658	0.299	1	14	1	14	4	18	1.317	1.089	5	22	1.153	0.846
340	**0.282**	**0.412**	**0.839**	**0.618**	**0.341**	**1**	**16**	**1**	**16**	**2**	**22**	**0.941**	**0.882**	**4**	**22**	**0.889**	**0.738**
341	0.351	0.464	1.070	0.797	0.404	1	21	1	5	5	22	1.206	1.119	7	22	1.136	0.944
342	0.586	0.645	1.609	1.151	0.615	2	22	1	22	8	22	1.676	1.314	11	22	1.642	1.23

Results

Plot system ver. Apr 29 2014 15:28:09

Laser:			
rms size	$<x^2>_0$=0.38400,	$<y^2>_0$=0.39700	[mm]
Electron beam:			
Momentum gun	5.92400	± 0.0250	[MeV/c]
Momentum booster	21.21300	± 0.0640	[MeV/c]
σ_{yag}	0.32870		[mm]
σ_{scan}	0.32948		[mm]
divergence	0.28980		[mrad]
covariance	-0.08415		[mm mrad]
sheared div	0.04512		[mrad]
LDrift	2.64700		[m]
β	2.40611		[mm]
γ	1.86145		[mrad]
α	1.86517		[mm mrad]
$\beta\gamma-\alpha^2$	1.00000		
$\varepsilon^{scaled}_{sheared}$	**1.633**		**[mm mrad]**
$\varepsilon^{noscaled}_{2D}$	**1.873**		**[mm mrad]**
$\varepsilon^{scaled}_{2D}$	**1.868**		**[mm mrad]**

Comments: no comm



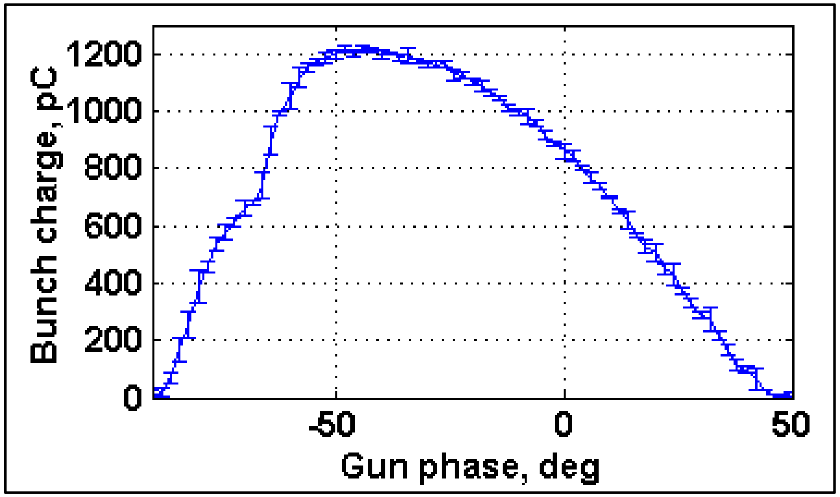
Electron beam based phase stability measurements for Gun 4.4

> Gun operation parameters

- 6.5 MW in the gun
- 400 μs RF pulse length
- Gun is slightly overheated

> Phase stability measurements based on:

- charge vs. gun phase dependence
- charge fluctuation due to gun phase jitter

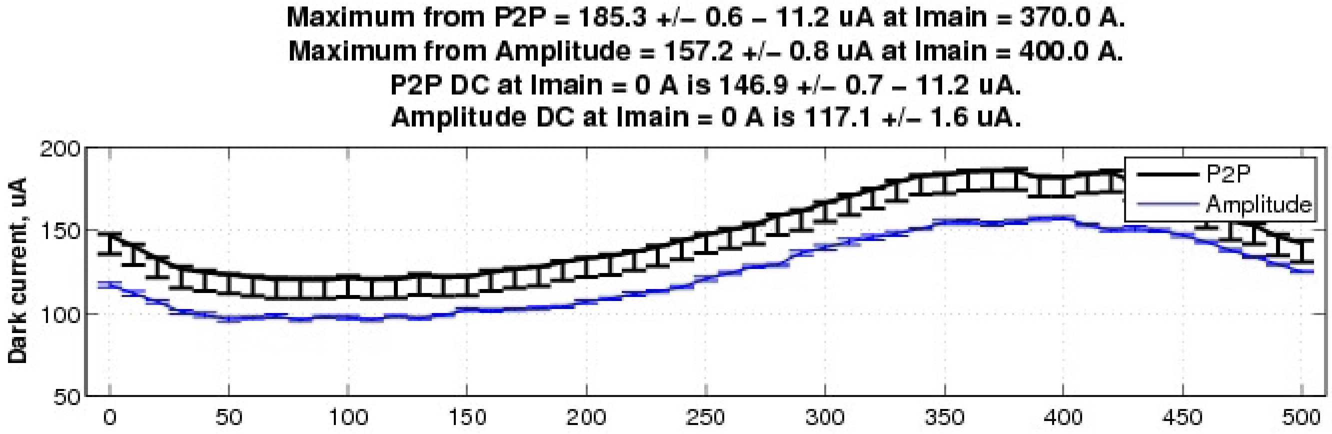


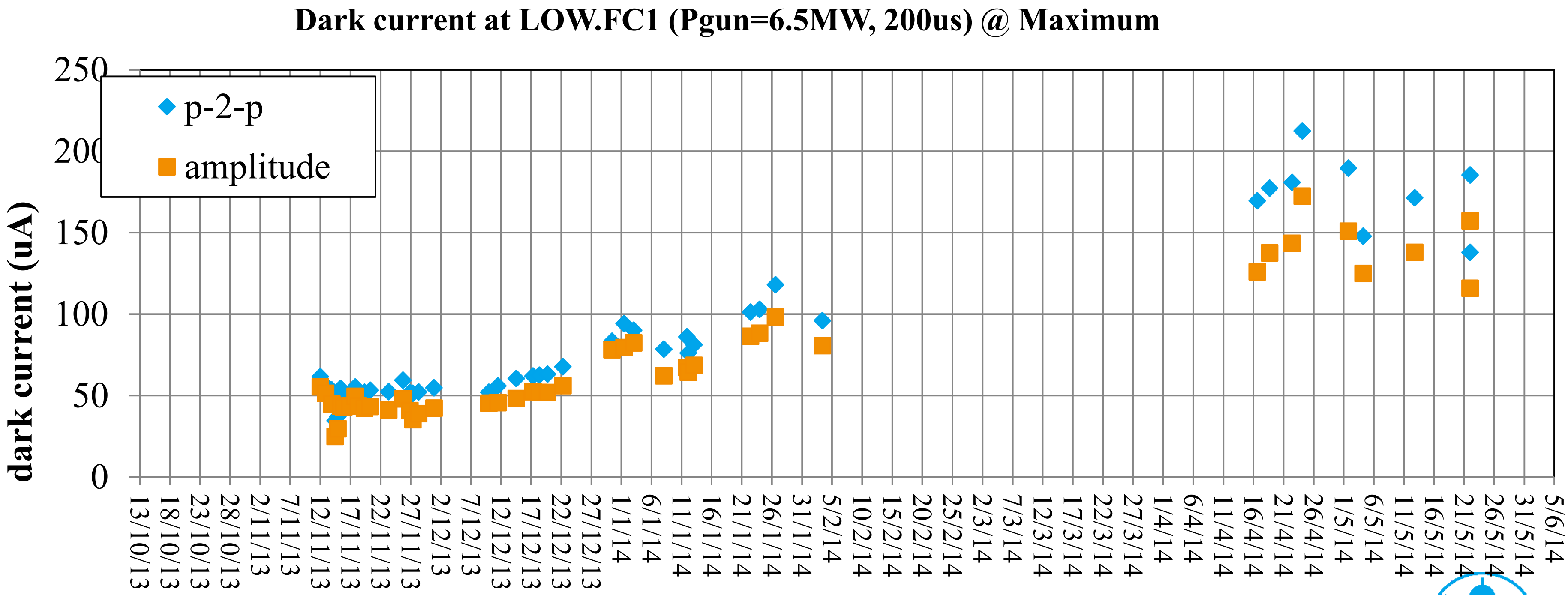
Gun phase jitter visible by beam includes RF phase jitter and gun temperature fluctuations

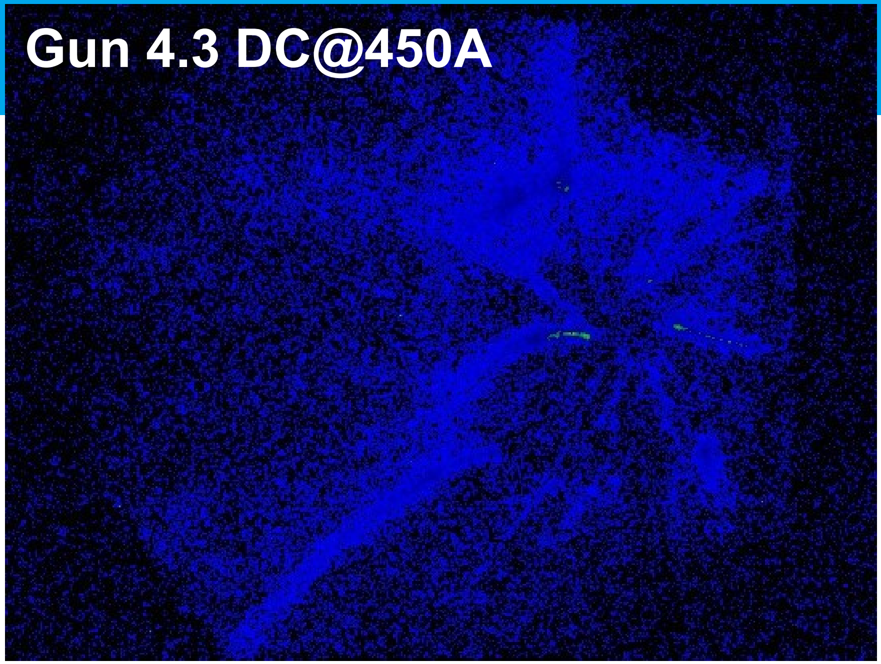
	Current WCS*	New WCS (test setup)
FB off	0.598 deg	0.475 deg
FB on	0.211 deg	**0.140** deg

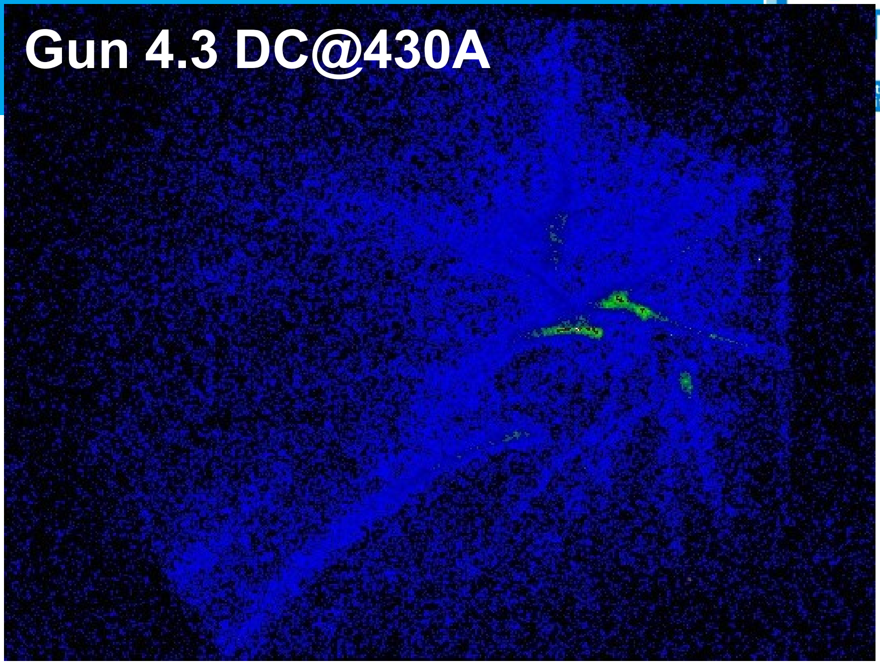
* WCS = water cooling system

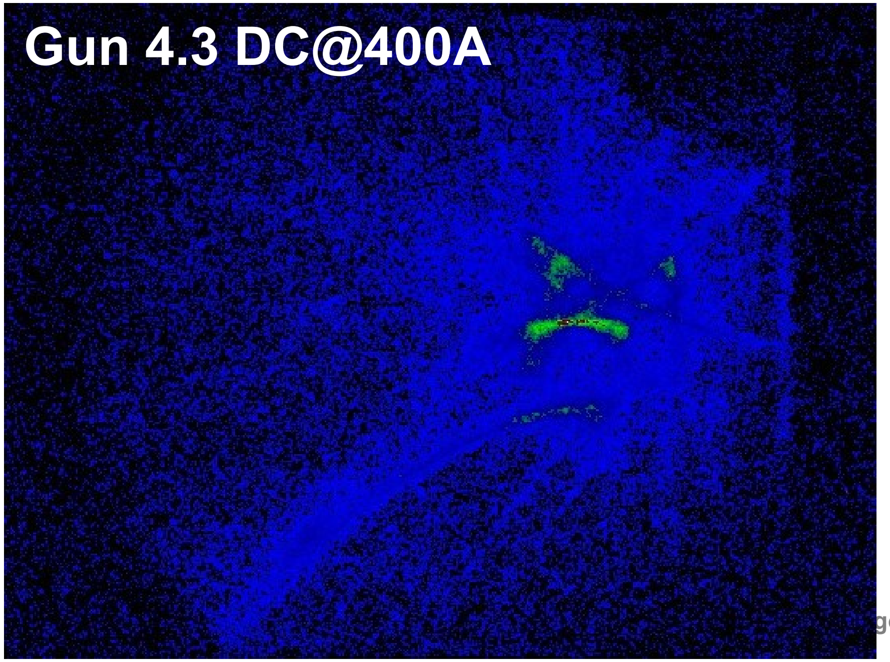
Example of dark current observations for gun

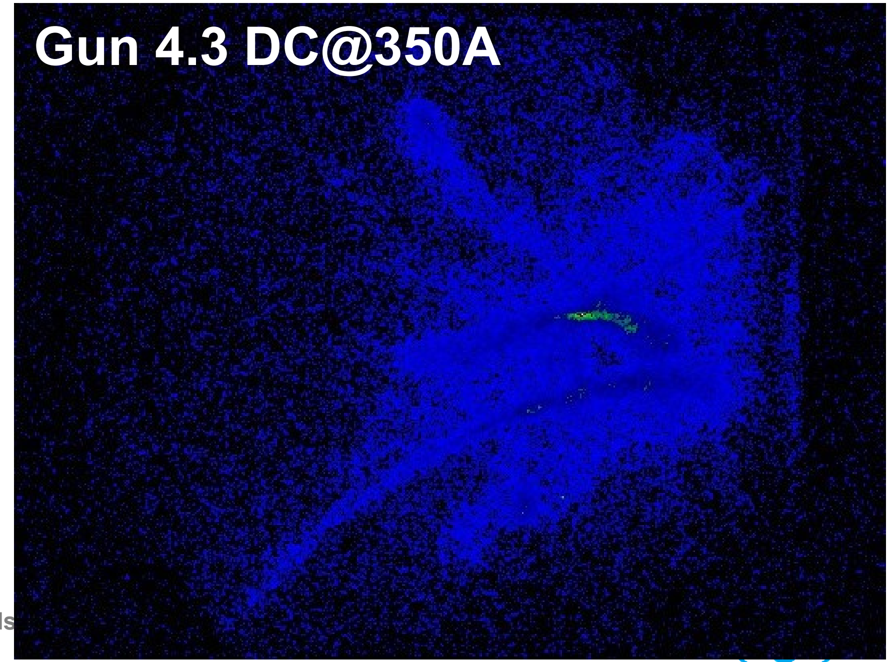





Gun 4.3 DC@450A


Gun 4.3 DC@430A


Gun 4.3 DC@400A


Gun 4.3 DC@350A

History of guns operated at PITZ

Gun prototype	Period of location at PITZ	Cleaned by:	Cathode area design	Water cooling channels design	Comment
Gun 1	Jan 2004 - Oct 2005	HPWR	Watchband	13 channels, common I/O volumes	
Gun 2	Dec 2001 – Nov 2003	HPWR	Watchband	13 channels, common I/O volumes	• opening the gun showed damages in the cathode spring area
Gun 3.1 *	Mar 2006 - Nov 2006 Nov 2012 - Feb 2013	HPWR	Watchband	8 channels, common I/O volumes	• cathode problem • **currently installed at FLASH**
Gun 3.2	Apr 2007 - Aug 2007	HPWR	Watchband	8 channels, common I/O volumes	• showed extreme traces from dark current emission as well as damages in the cathode spring area • heavy damage of the cathode spring
Gun 4.1	Dec 2009 - Jun 2012	Dry-ice	Watchband	14 channels, separate I/O volumes	• the gun with which one the best emittance was achieved
Gun 4.2	Mar 2008 - Oct 2009 Jul 2014 **– current time**	Dry-ice	Watchband / Contact stripe	14 channels, separate I/O volumes	• damages in the cathode spring area after dismounting from FLASH due to IL problems • new RF spring design (contact stripe) implemented in autumn 2012
Gun 4.3 **	Mar 2013 - Jul 2013	Dry-ice	Contact stripe	14 channels, separate I/O volumes	• problem in the cathode holder nose area discovered -> new RF spring design (contact stripe) was applied • **currently installed at XFEL**
Gun 4.4	Oct 2013 - May 2014	Dry-ice	Contact stripe	14 channels, separate I/O volumes	• first gun with new RF spring design (contact stripe) from the beginning • cathode spring replaced by gold-plated spring

Acknowledgements

PITZ Team

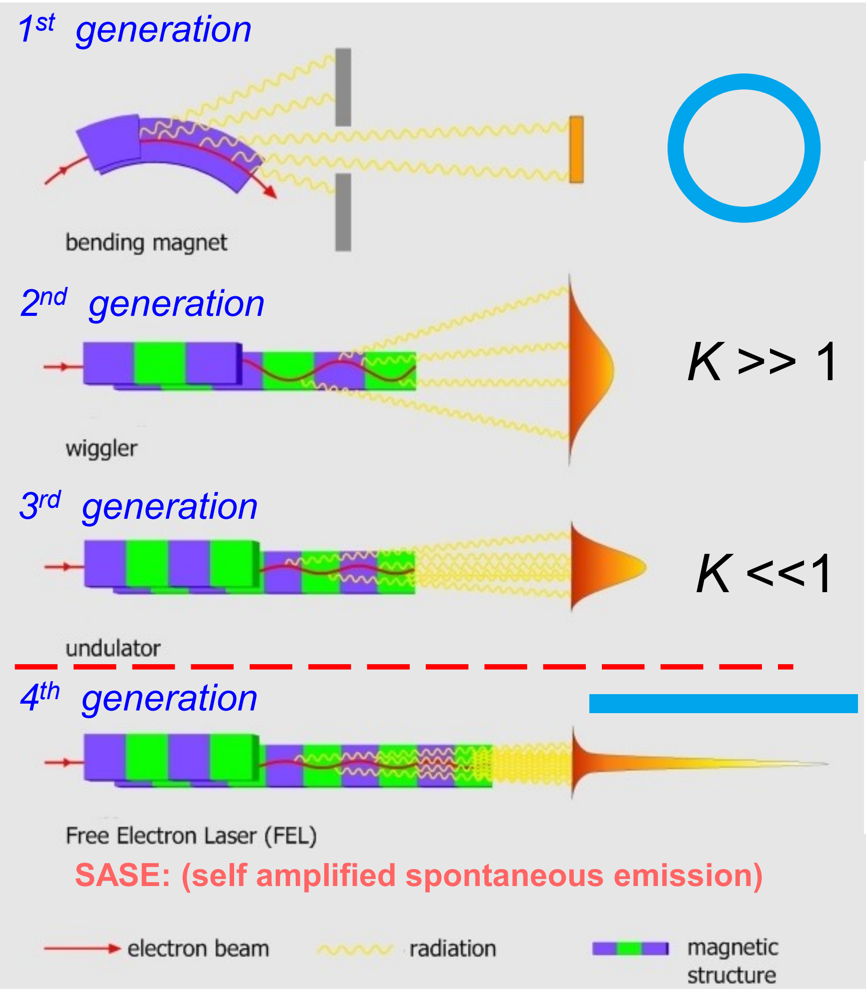
DESY Zeuthen:
F. Stephan, M. Krasilnikov, G. Asova, H.-J. Grabosch, M. Groß, L. Hakobyan, I. Isaev, Y. Ivanisenko, L. Jachmann, M. Khojoyan, G. Klemz, W. Köhler, M. Krasilnikov, M. Mahgoub, D. Malyutin, M. Nozdrin, A. Oppelt, M. Otevrel, B. Petrosyan, S. Rimjaem, A. Shapovalov,, G. Vashchenko, S. Weidinger, R. Wenndorff
DESY, Hamburg: K. Flöttmann, M. Hoffmann, S. Lederer, H. Schlarb, S. Schreiber
MBI, Berlin: I. Templin, I. Will
INR, Moscow: V. Paramonov
HZB, Berlin: D. Richter

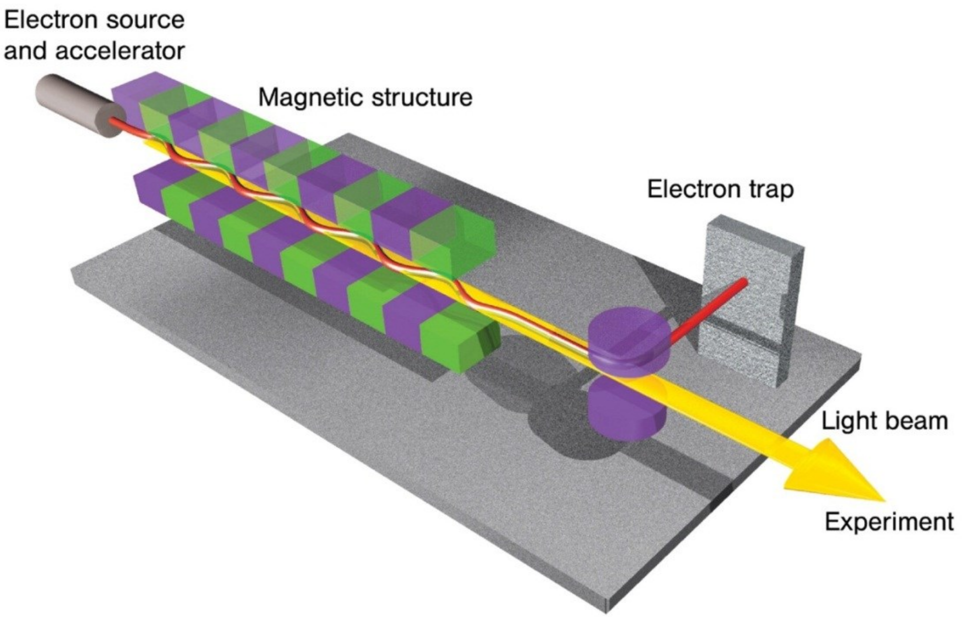
With contributions from PITZ partners:
DESY (Hamburg); Hamburg University; HZB (Berlin); INFN (Milan, Italy); INR (Troitsk, Russia); INRNE (Sofia, Bulgaria); LAL(Orsay, France); MBI(Berlin); STFC (Daresbury, UK); TUD (Darmstadt);
ThEP (Thailand); YERPHI (Yerevan, Armenia)

Thank you for your attention.

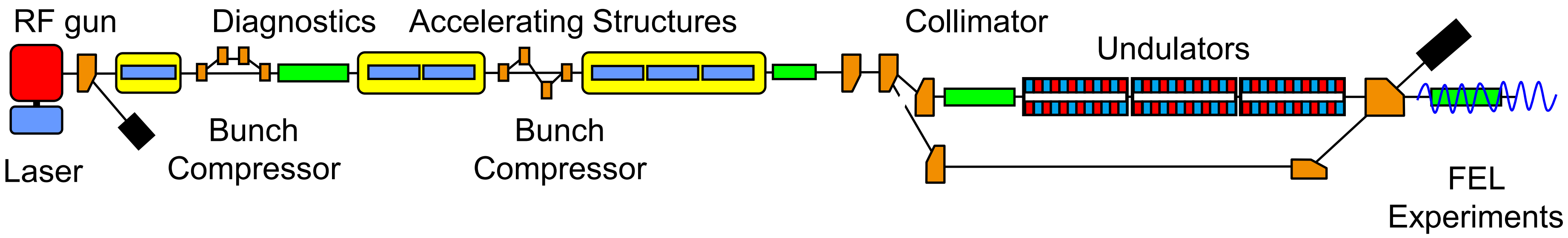
Free Electron Lasers

$$\lambda_L = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \qquad K \equiv \frac{e B \lambda_u}{2\pi\beta m_e c}$$

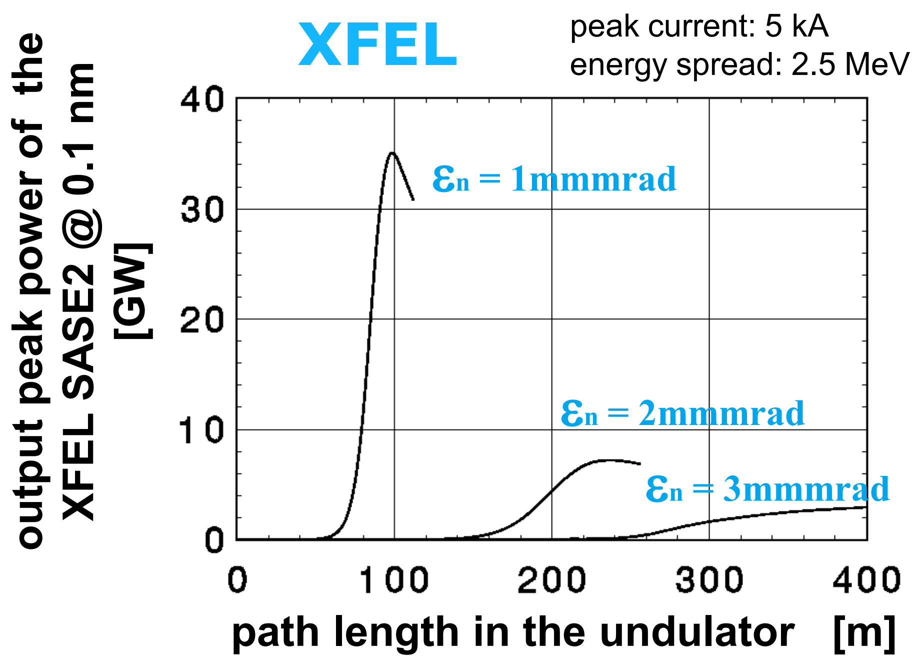




Free Electron Lasers



The beam quality degrades as the beam propagates downstream. An FEL needs coherent electrons.

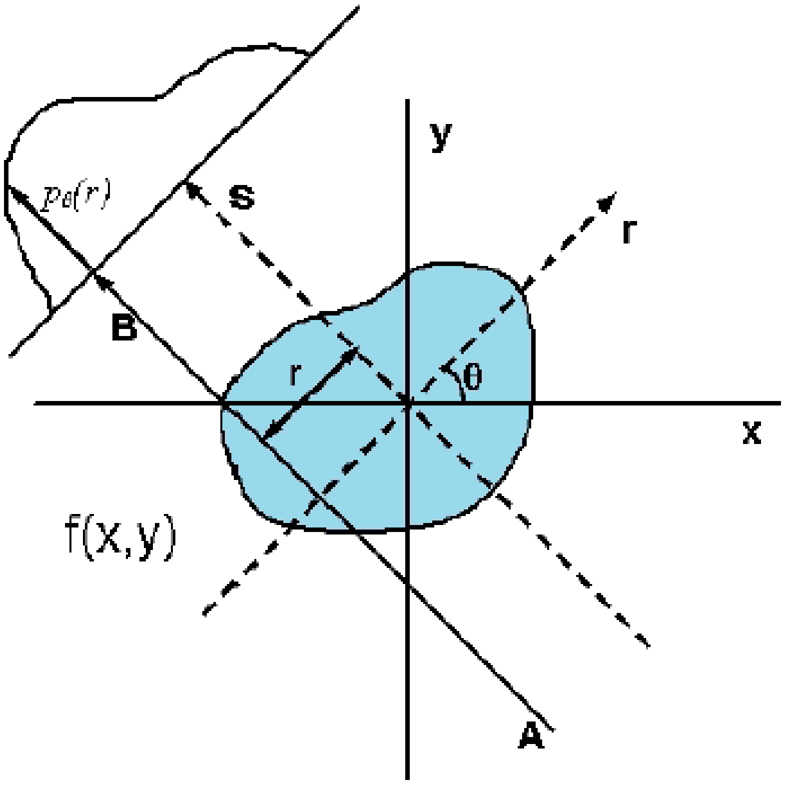


Emittance:

ε_n < 1.0mmmrad

@ the injector

Bunch length, longitudinal phase space (using dipole)



For example:
X-ray absorption by the material

We have unknown object $f(x, y)$.

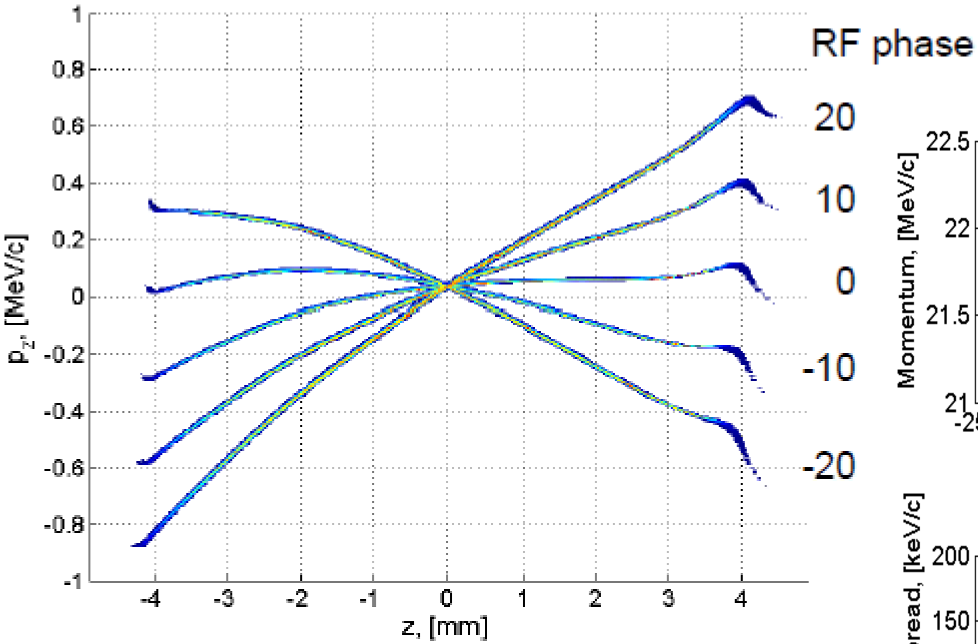
We can measure projection of this object $p_\theta(r)$ at different angle θ.

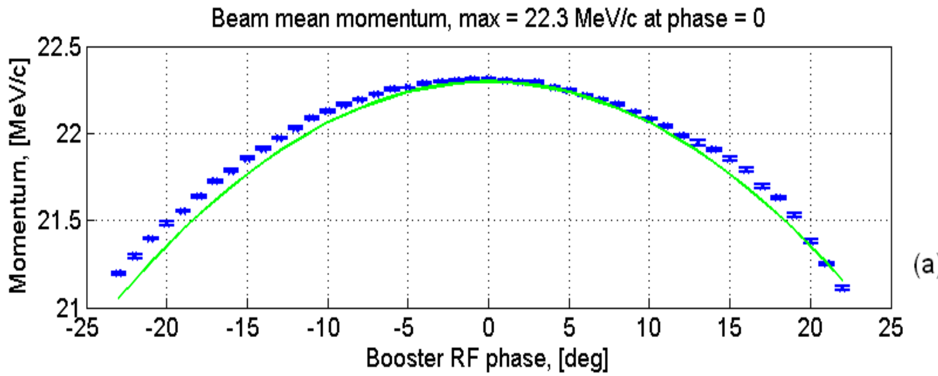
Resulted $p_\theta(r)$ is called tomography transformation of the object $f(x, y)$.

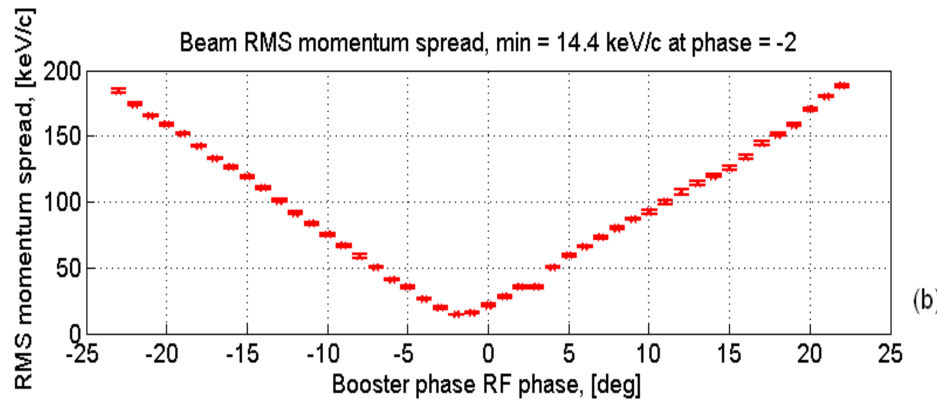
Procedure to restore unknown object from the set of projections is called inverse tomography transformation.

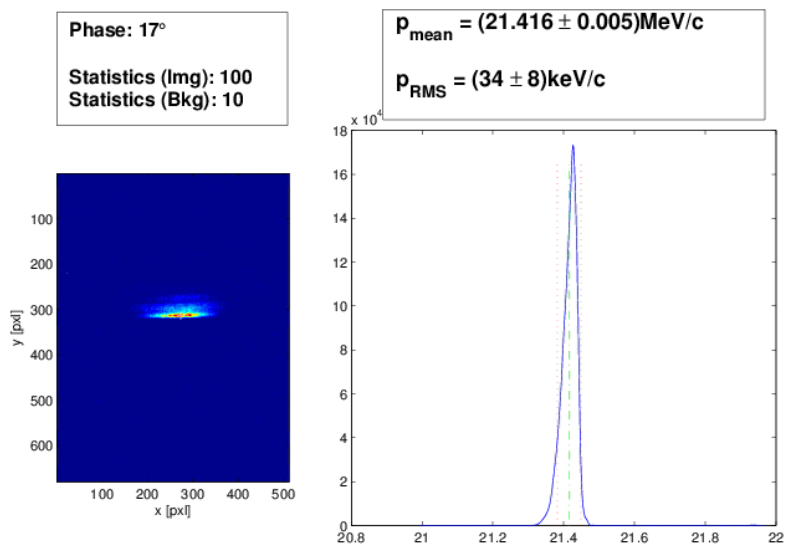
This procedures can be applied to the longitudinal phase space image.

Bunch length, longitudinal phase space (using dipole)

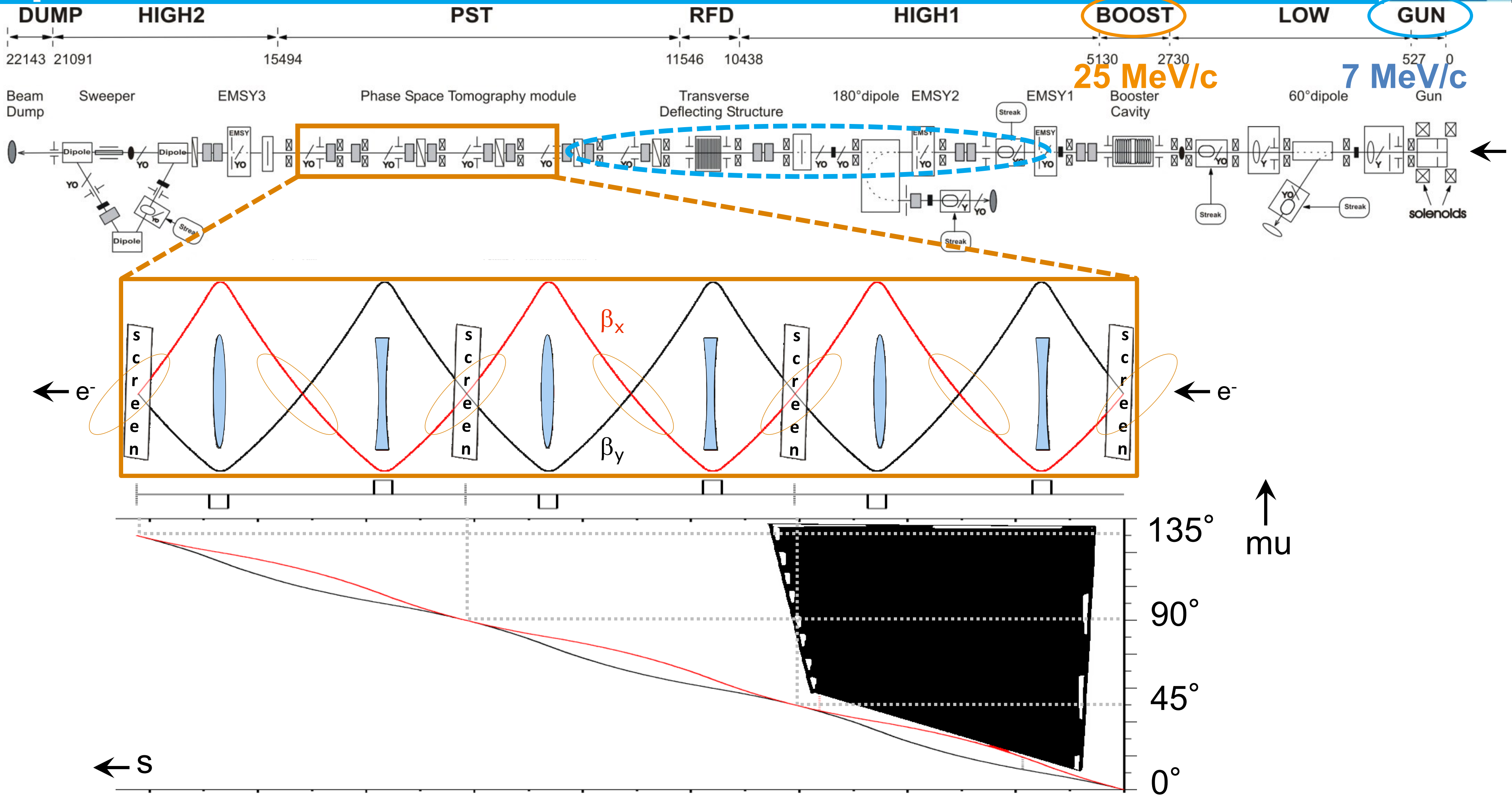






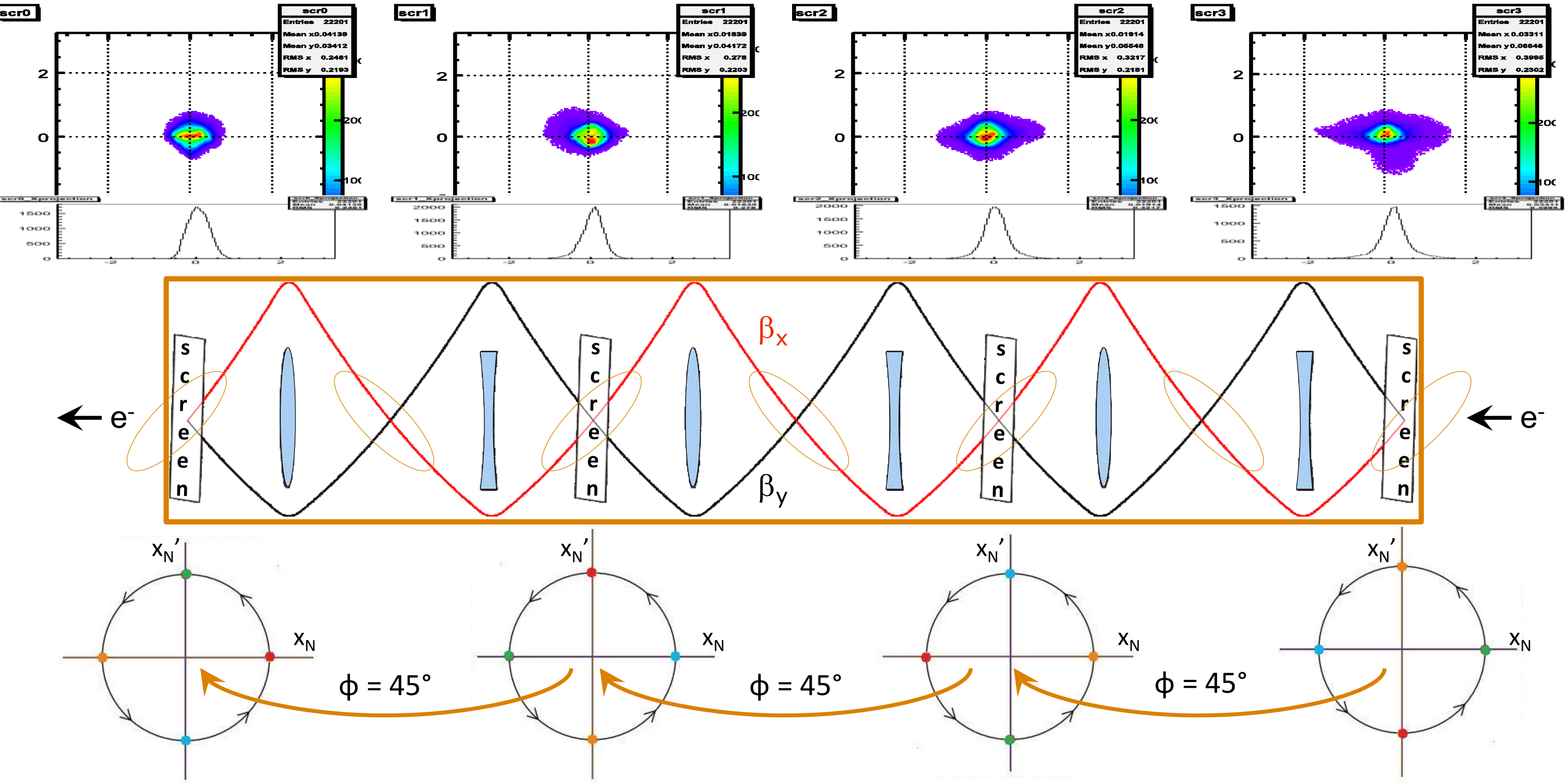


Tomographic reconstruction of the transverse phase space at PITZ



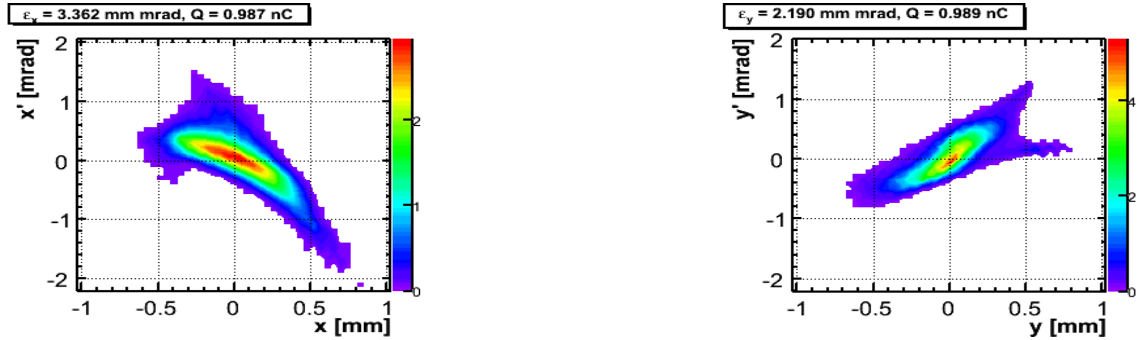
1) Quadrupoles form a FODO lattice and oppose a complete 180° rotation of the beam in the normalized transverse phase space

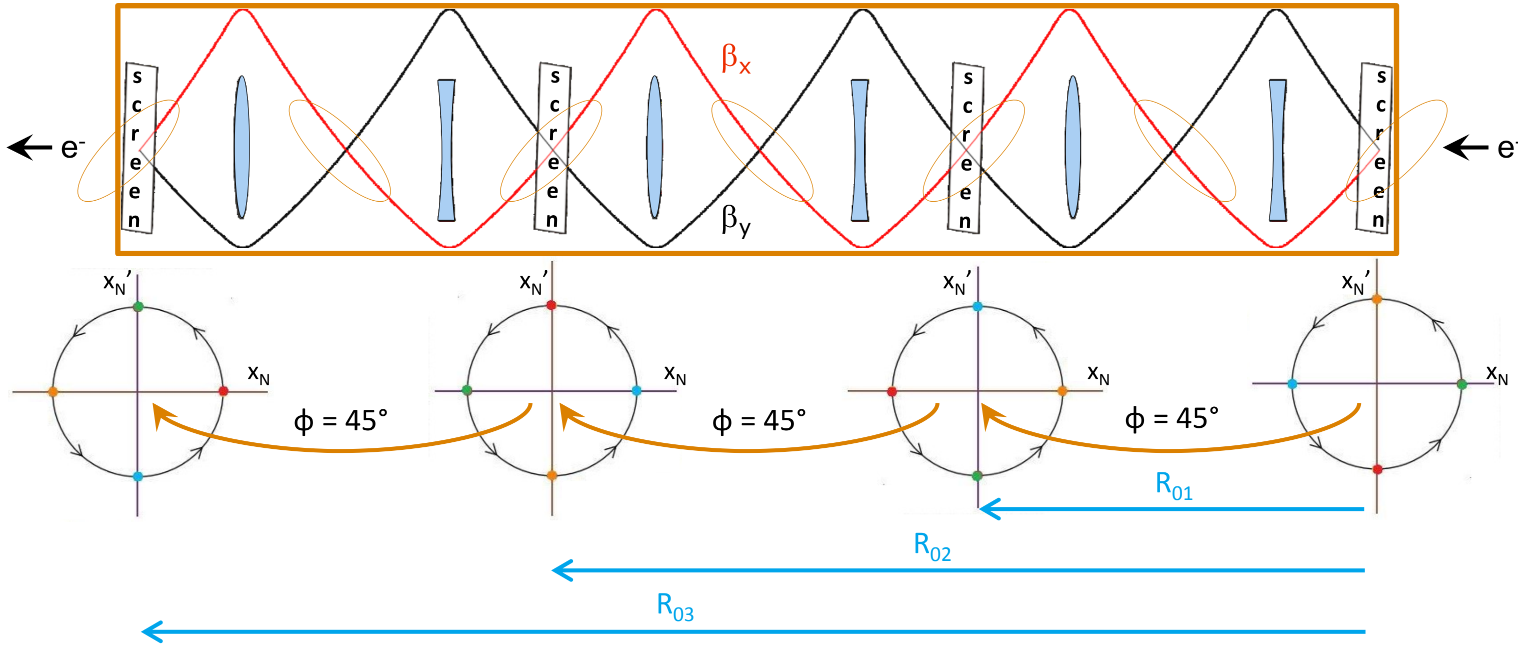
Tomographic reconstruction of the transverse phase space at PITZ



2) At equidistant phase advance values (≈ rotation angles) the screens capture the beam profile, creating projections of both transverse planes

Tomographic reconstruction of the transverse phase space at PITZ





3) Calculate the transfer matrices (→ description of the phase space transformations) and reconstruct with the Maximum ENTropy algorithm