Stability and performance studies of the PITZ photoelectron gun.

- Motivation
- Introduction to PITZ
- Reliability: Gun conditioning
- Stability: RF phase jitter
- Performance: Electron beam asymmetry
- Summary and conclusions

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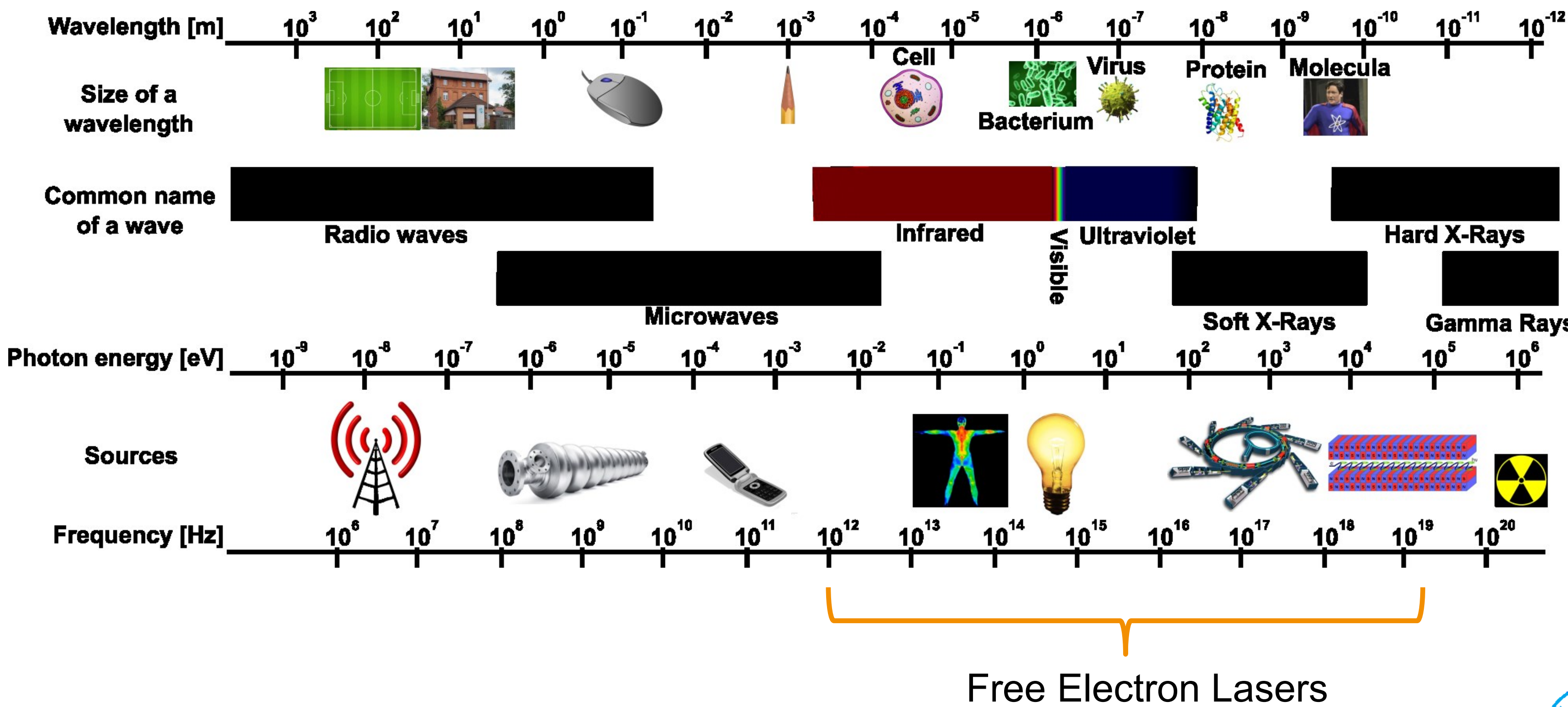
PhD defense
Joint DESY and University of Hamburg
Accelerator Physics Seminar
Hamburg, 27th of September 2017

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
HELMHOLTZ | ASSOCIATION
DESY
PITZ Photo Injector Test Facility Zeuthen

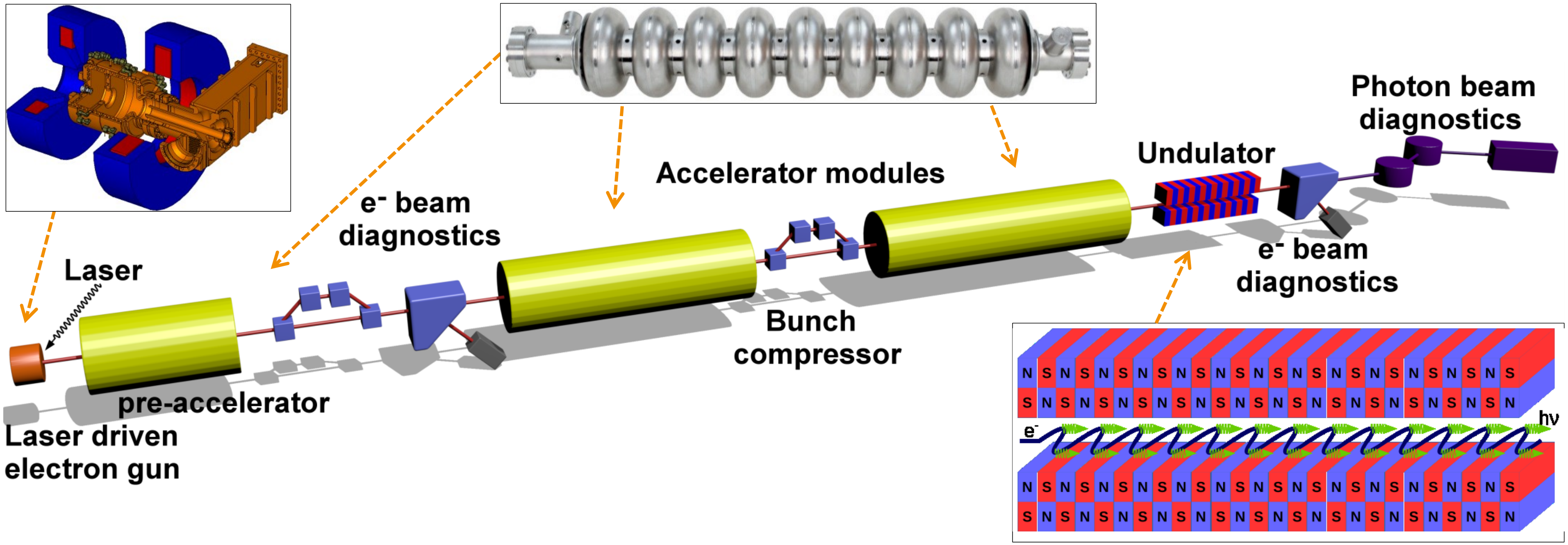
Motivation: Why we need light sources?

Study of the microscopic structures is of the great importance for the several areas of the modern natural science.

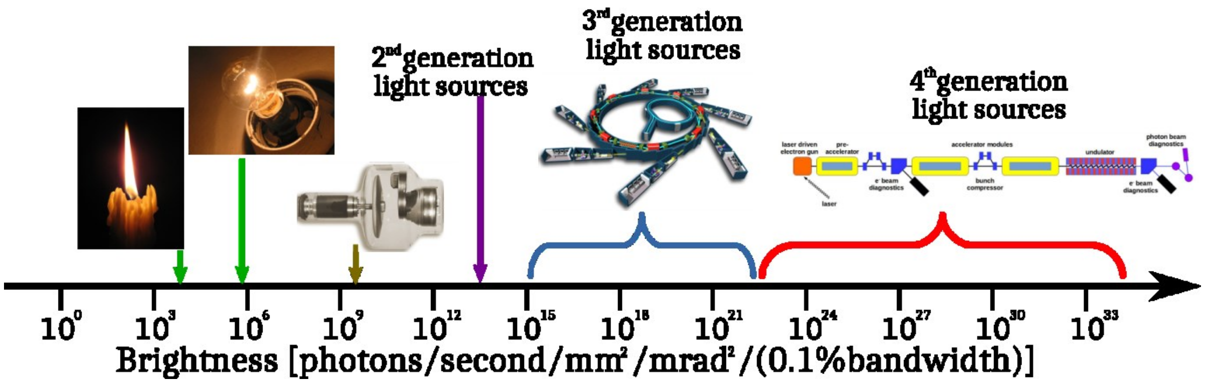
It gives us a unique opportunity to observe the highly complex tiny structures of our world.



Free Electron Lasers (FELs)



SASE FEL ➔ High phase space density of electron bunches already from the source ➔ Small transverse emittance (ε) and high current (I) ➔ High brightness (B) electron source



$$B = \frac{2I}{\varepsilon_{n,x}\varepsilon_{n,y}}$$

My Thesis and PITZ Goals

> The Photo Injector Test facility at DESY, Zeuthen site (PITZ) is dedicated to develop and test RF guns for high brightness beams including all subsystems

> PITZ goals:

- **Development** of an electron source for the European XFEL
- Extensive **R&D on photo-injectors** (in parallel to European XFEL and FLASH operation)
- Benchmark **theoretical understanding** of photo-injectors
- **Preparation** and **characterization** of RF guns for subsequent operation at FLASH / XFEL
- **Testing** of new developments (laser, cathodes, beam diagnostics)

> My thesis goals:

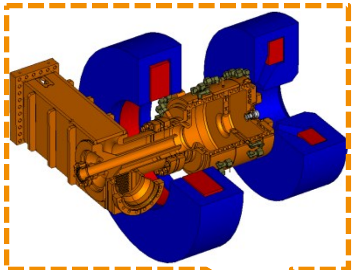
- Gun **reliability** studies:
  - understanding of physical processes in the gun (**conditioning process**, parameters adjustments)
- Gun **stability** studies:
  - investigations on the beam production behavior (**RF phase jitter studies**)
- Gun **performance** studies:
  - comprehension of the discrepancies between models and experiments (**beam imperfections studies**)

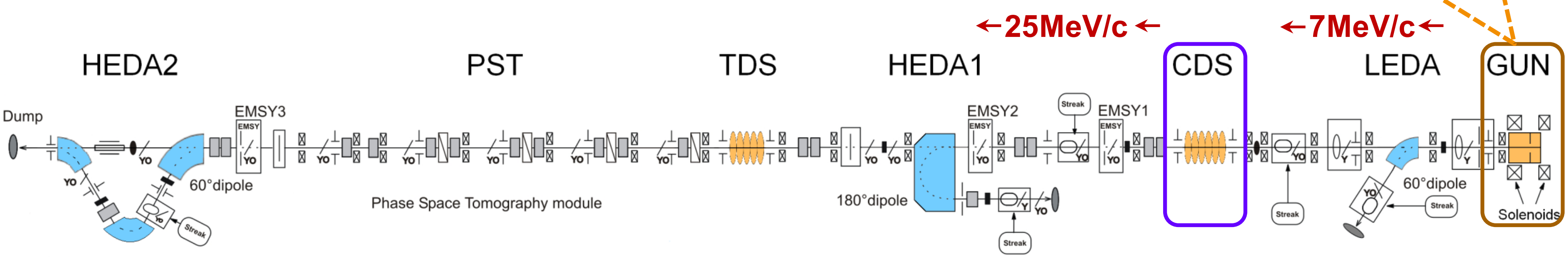
PITZ facility

- RF photoelectron gun
- Booster
- Electron beam Diagnostics:
  - slit scan (transverse phase space)
  - streak camera, TDS, dipole (longitudinal phase space)
  - screen stations (beam shape)
  - tomography (transverse phase space)
- New developments (e.g. plasma acceleration)

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	≤650
Repetition rate, Hz	10
Optimized emittance (1nC), mm mrad	<0.9





Photoelectron gun setup

PITZ photoelectron gun setup consists of:

> RF cavity

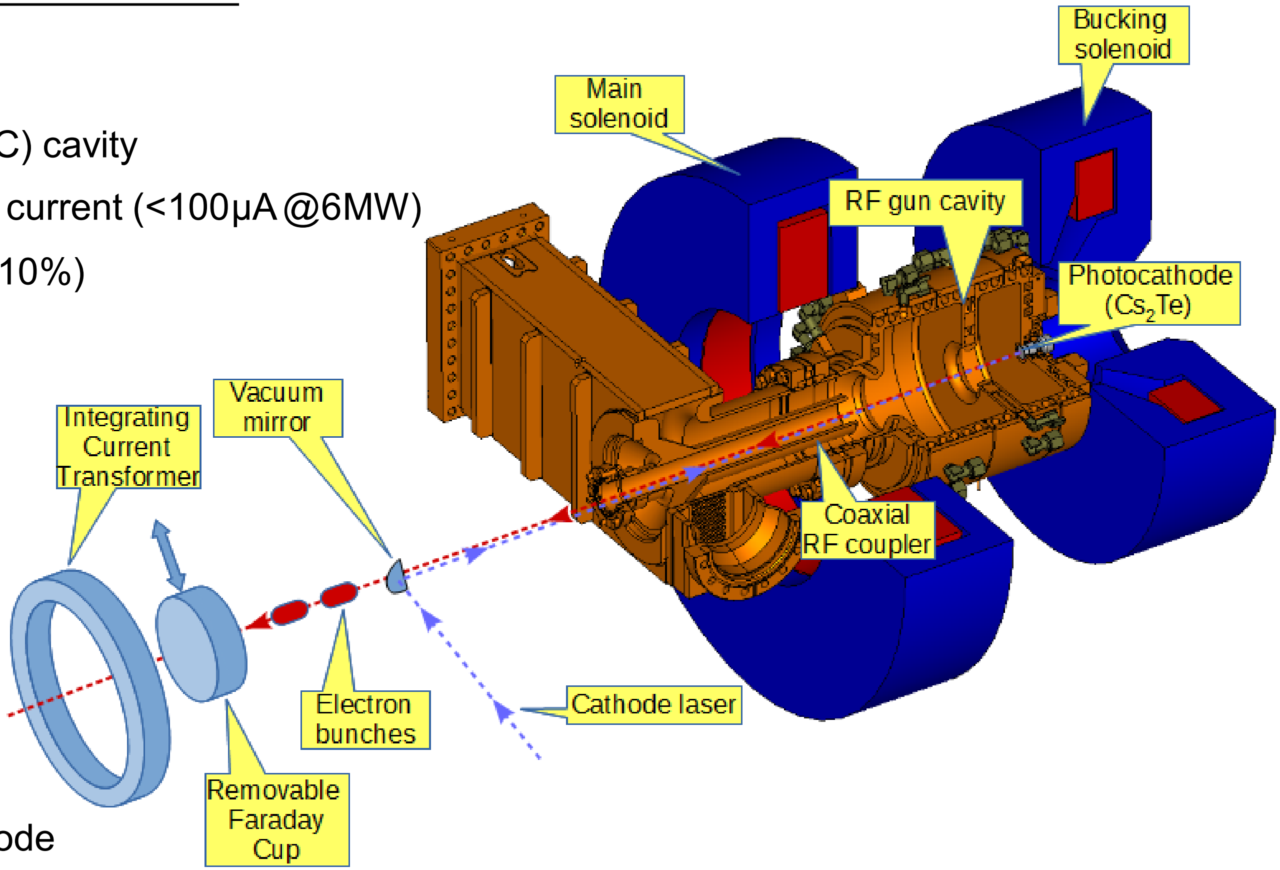
- L-band **1.6-cell** copper (OFHC) cavity
- **Dry-ice cleaning** → low dark current (<100μA @6MW)
- **Cs_2Te** photocathode (QE ~5-10%) with load-lock system
- LLRF control for amplitude and phase stability

> Solenoids

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

> Photocathode laser

- **Pulse train structure**
- Micropulses temporally and spatially shaped



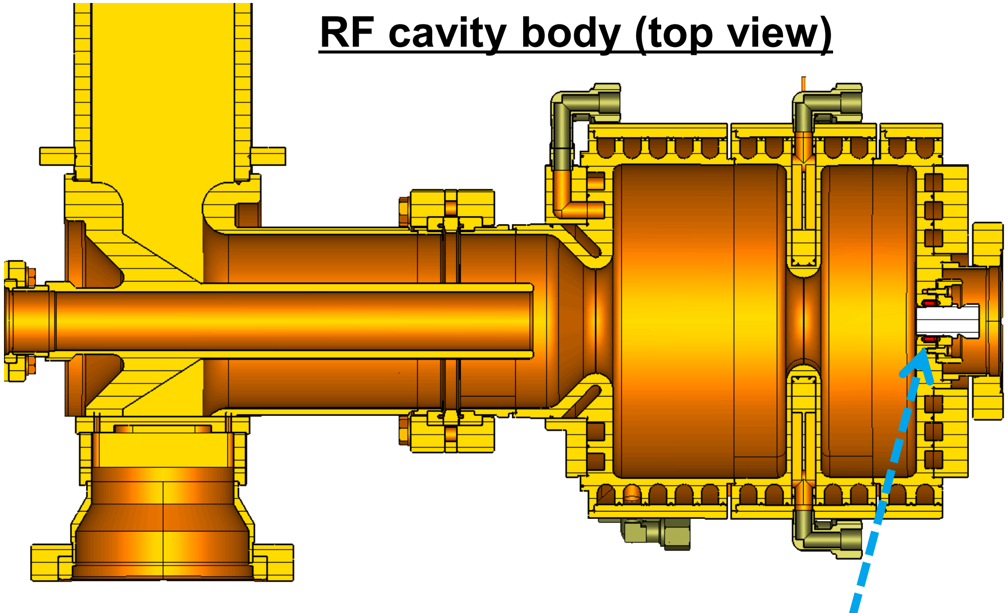
Main parameters

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

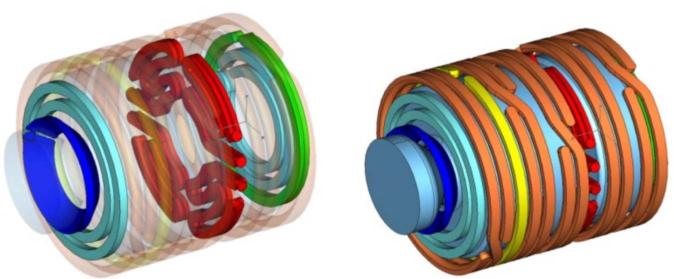
*** The European XFEL requirements**

The RF photo gun cavity operates with a standing wave regime in the π-mode.

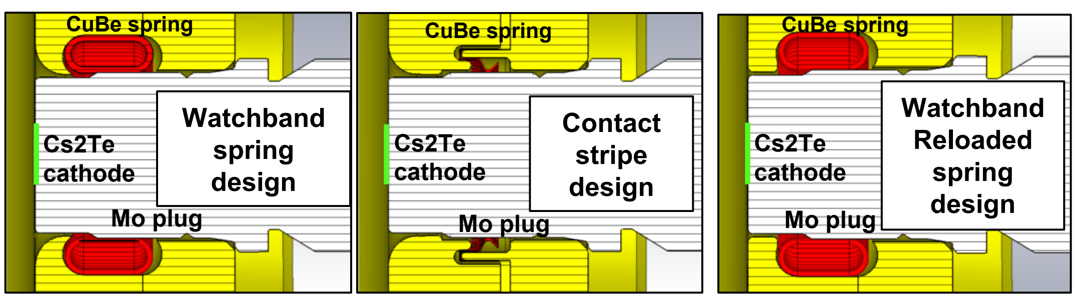
RF cavity body (top view)



RF cavity water cooling channels
(Gun 4 type)



Three designs of the cathode area

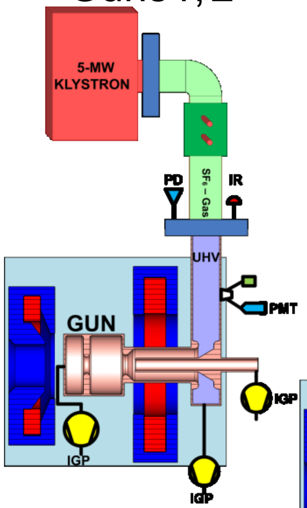


Gun Reliability

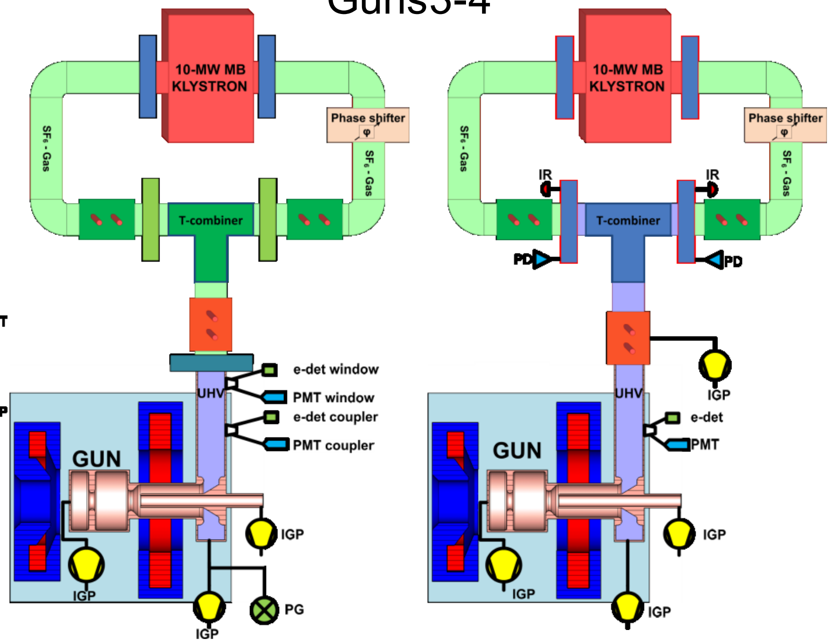
History of guns operated at PITZ

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 emittances were achieved
Gun 4.2	Mar 2008 - Oct 2009 Jul 2014 - Oct 2015	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
Gun 4.6	Mar 2016 - **current time**	Dry-ice	Watchband reloaded	14 channels, separate I/O volumes	• first gun with watchband reloaded RF spring design from the beginning • T-Combiner with optimized RF design for best window position

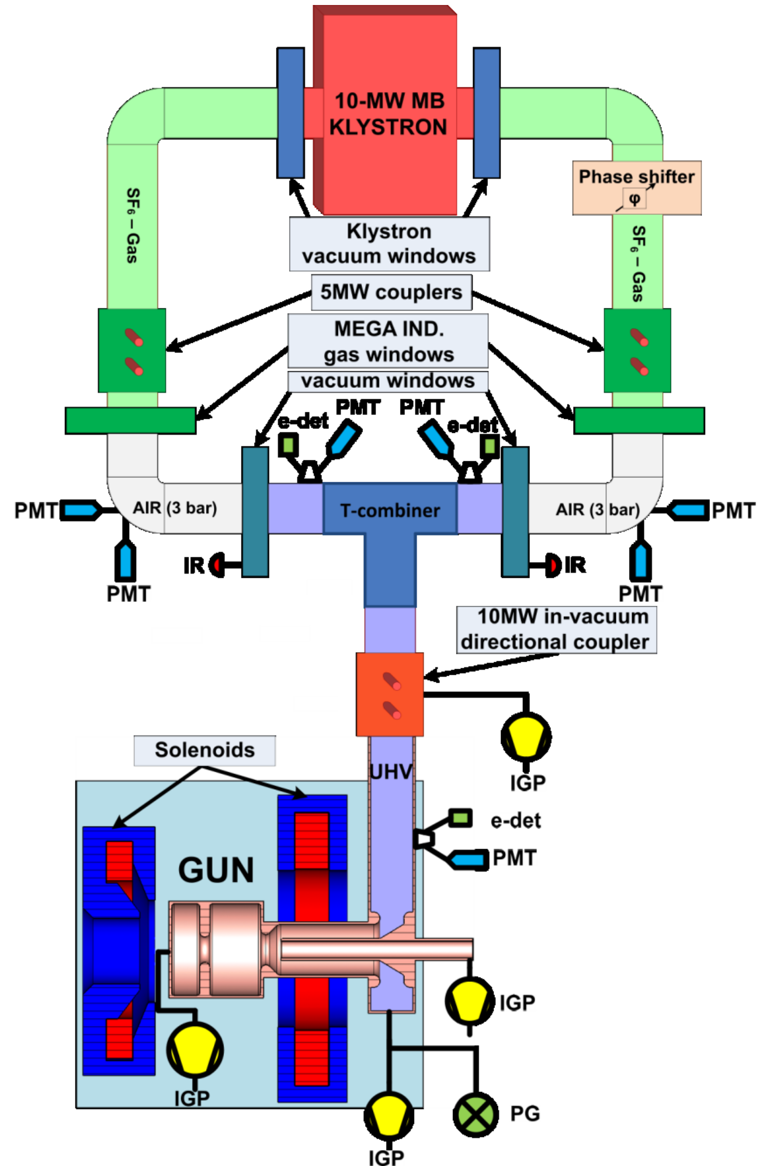
Year 2001-2005, Guns1,2



Year 2005-2014, Guns3-4



Year 2016-2017 Gun4.6



The interlock (IL) system prevents serious damage of the cavity and auxiliary systems.

The IL system consists of:

- **Fast** signal propagation part: total delay **1.1msec** (PMT, e-det, IR…)
- **Slow** signal propagation part: total delay **4.8msec** (PG, IGP)

PMT - Photomultiplier tube, e-det – Electron detector, PD – Photodiode,

IGP – Ion getter pump (pressure reading), PG - Pressure gauge, IR – Infrared detector

Gun cavity preparation - Conditioning

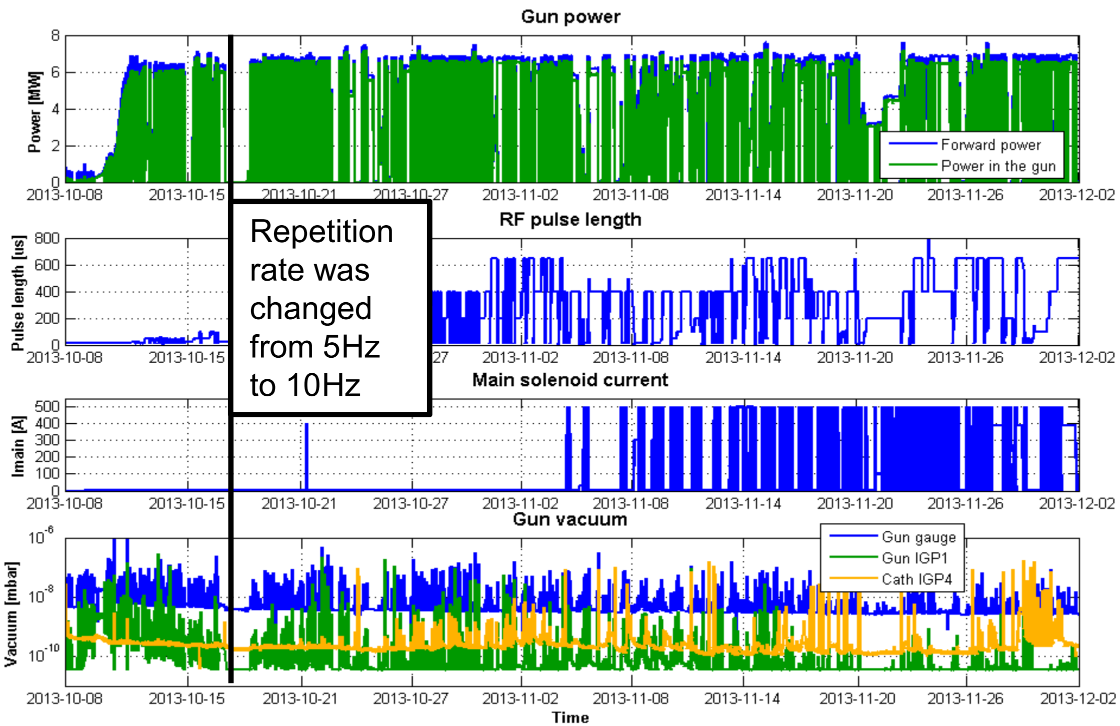
- **Conditioning** is an **RF cavity training** to get the highest possible accelerating gradients and achieve a stable operation at specification parameters.
- RF conditioning of a vacuum RF-component is a surface cleaning process using a low-density plasma within RF fields.
- Conditioning effect and progress **is judged by indirect and direct plasma density measurements** (biased e⁻ probes and photomultipliers) and direct measurement (a vacuum chamber pressure).
- **The main sources** of the particles for plasma are: *field emission* (**dark current**), *secondary emission* (**multipacting**) and ***outgassing***.

RF peak power

RF pulse length

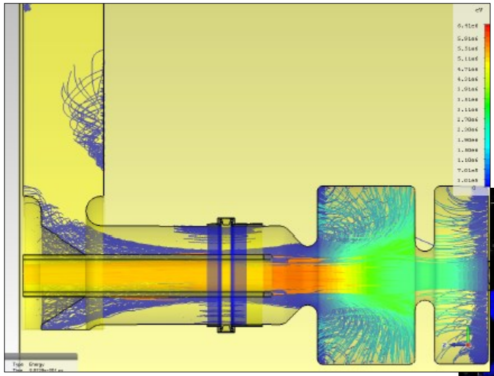
Main solenoid current

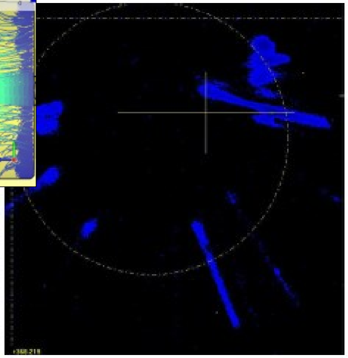
Vacuum level



Factors limiting conditioning: Dark current and Multipacting

- **The dark current** is unwanted electron current appeared in a cavity by a field emission.
  - The electron field emission is the main reason of dark current. It also causes breakdown and multipacting phenomena.
  - In case of **RF cavities** electron field emission happens under RF fields. It can be explained by **modified Fowler-Nordheim equation**:

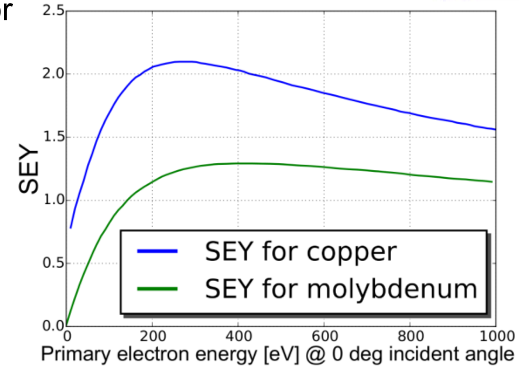




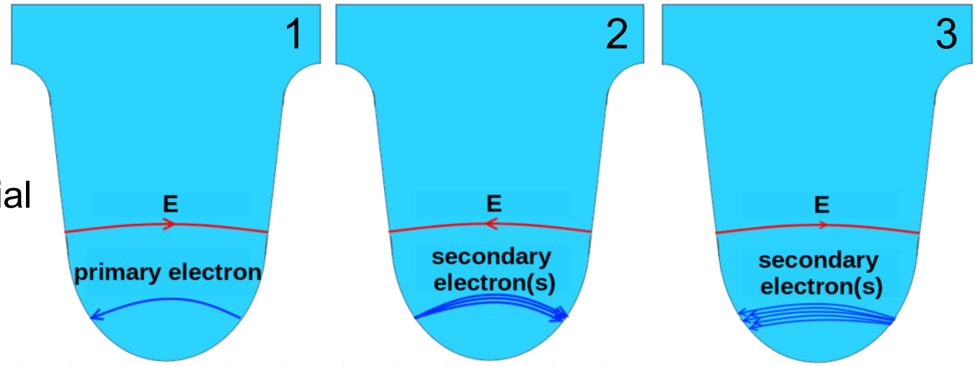
$$\bar{I}_{FN} \propto A_e \left(\beta E_0\right)^{2.5} \exp\left[\frac{1}{\beta E_0}\right]$$

$\bar{I}_{FN}$ - average field emission current [A]
A_e - emitting area [m^2]
E_0 - amplitude of the sinusoidal macroscopic surface field [V/m]
β - field enhancement factor

Ref. slac-pub-7684

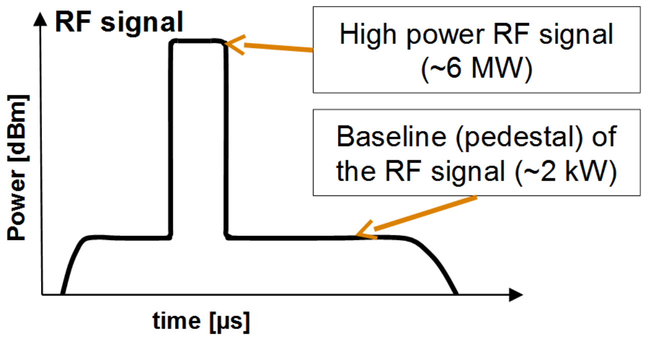


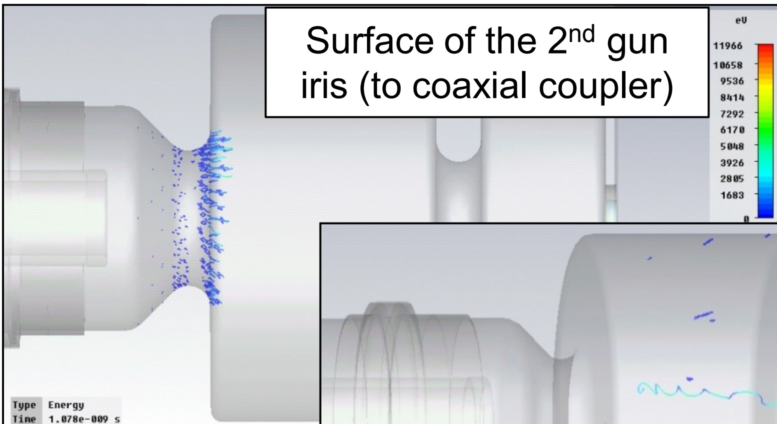
- **The multipactor discharge** (multipacting) is the phenomenon of a **resonant secondary electron emission** which occurs at certain conditions. Multipactor discharge depends on:
  - Field configuration
  - Cavity geometry
  - Secondary emission yield (SEY) of the cavity material

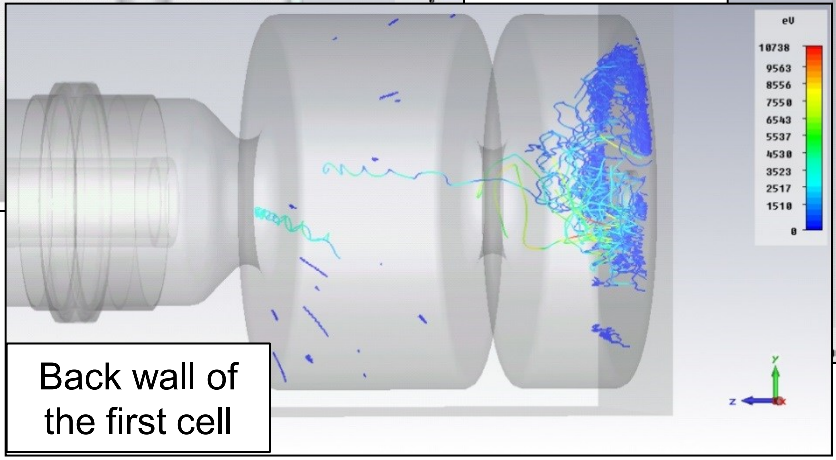


Multipacting simulations for the gun cavity and the gun coupler

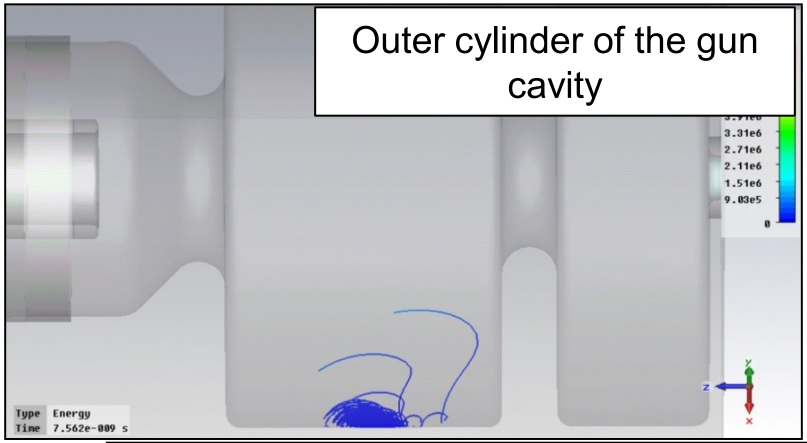
Multipacting trajectories at accelerating gradient at the cathode of 1MV/m (~2kW power in the gun)

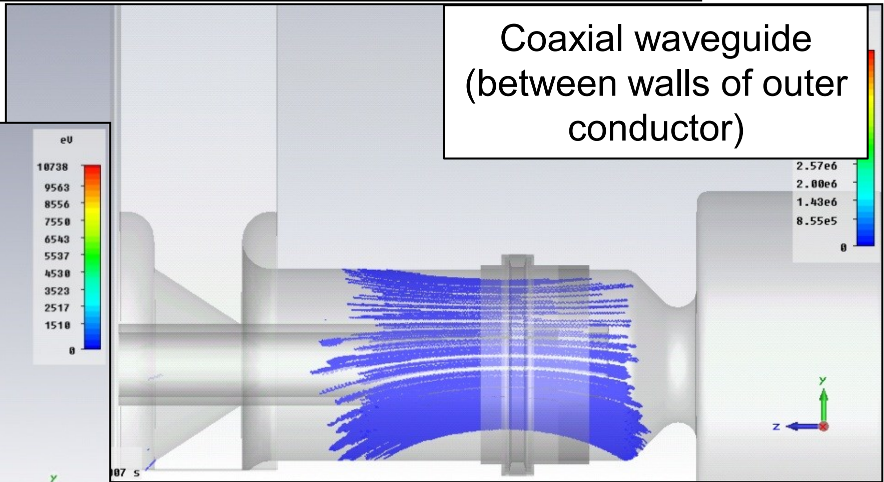






Multipacting trajectories at accelerating gradient at the cathode of 60MV/m (~6.5MW power in the gun)



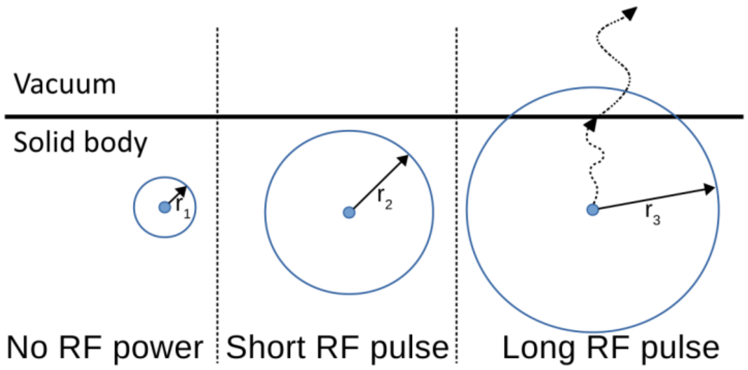


Multipacting is present in the gun but not preventing operation.

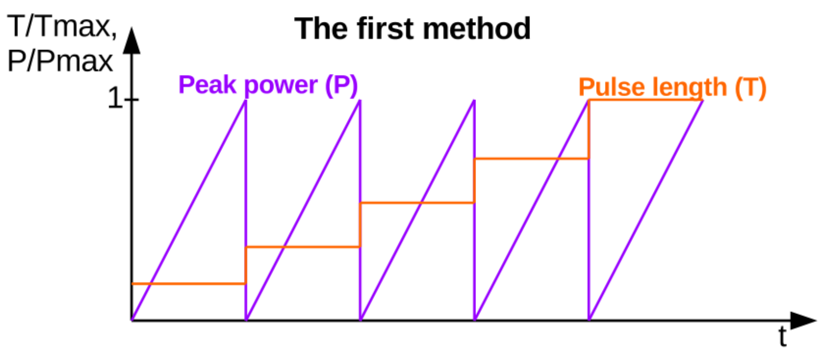
Outgassing and Conditioning procedure

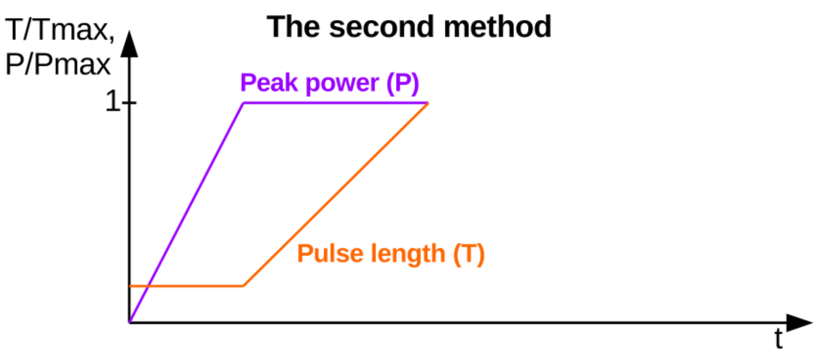
- **The outgassing process** in a solid bulk material consists of two steps:
  - gas particles diffusion from the solid body to the surface
  - desorbtion from surface

  By increasing the temperature, the speed of the gas escape increases exponentially



- **Conditioning procedure**



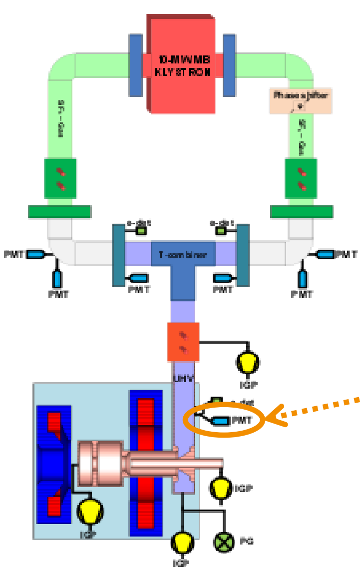


Ramp-up procedure:

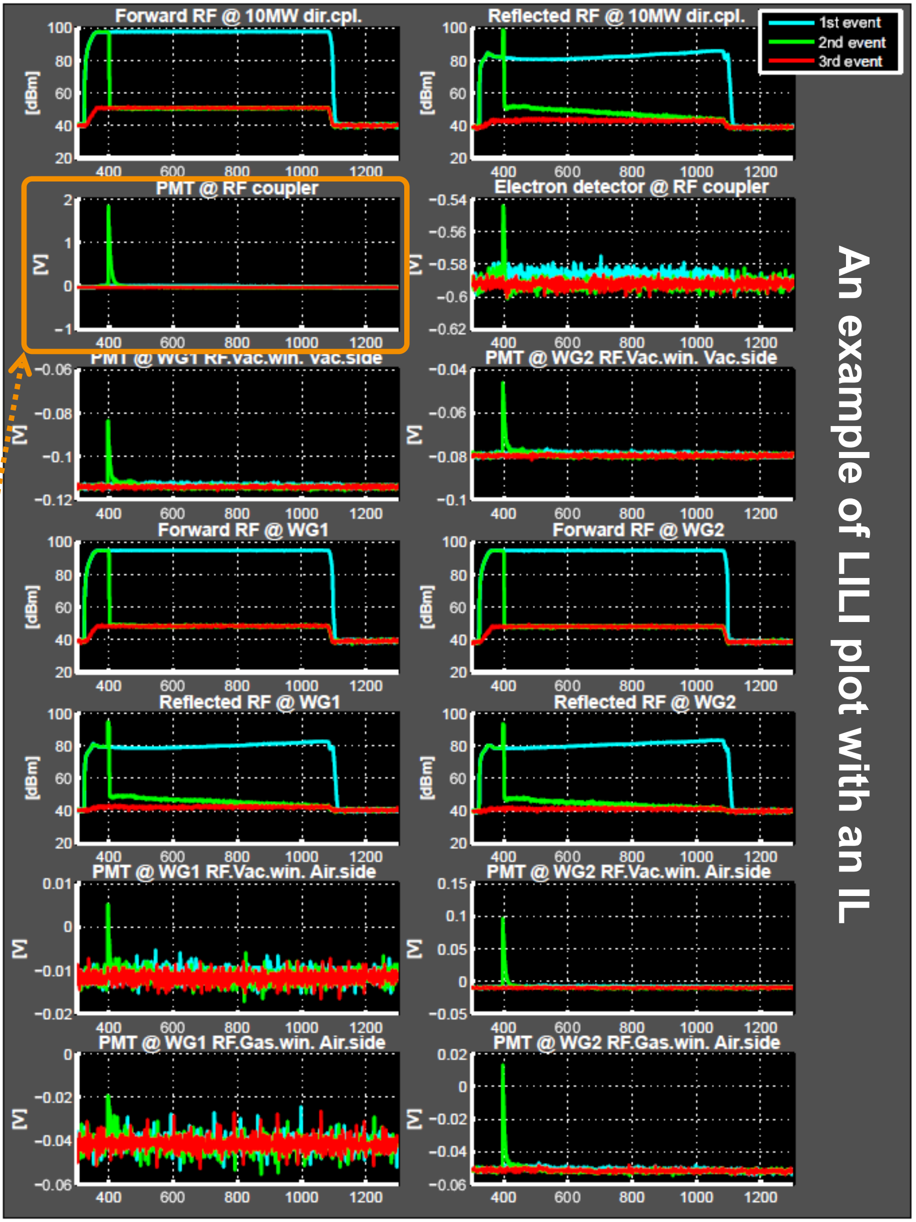
- RF power increase for new RF pulse length: **0.2MW / 15minutes**
- vacuum pressure **<10^{-7}mbar**
- In case of significant vacuum or other trips:
  - re-ramp RF power from 0MW, 10μs
- Initially, the RF gun solenoid is off (then sweep)
- No feedback

Development and Implementation of Last InterLock Investigator (LILI)

- LILI enables a detailed investigation of all possible interlocks.
- LILI operates with data stored in the DAQ system.
- Based on the analysis, corrections to the RF conditioning process can be introduced resulting in more efficient preparation of the gun cavity for its consequent operation.



The IL was triggered by the **PMT** located at the RF coupler at **5.7MW** peak power in the gun and **600μs** RF pulse length.



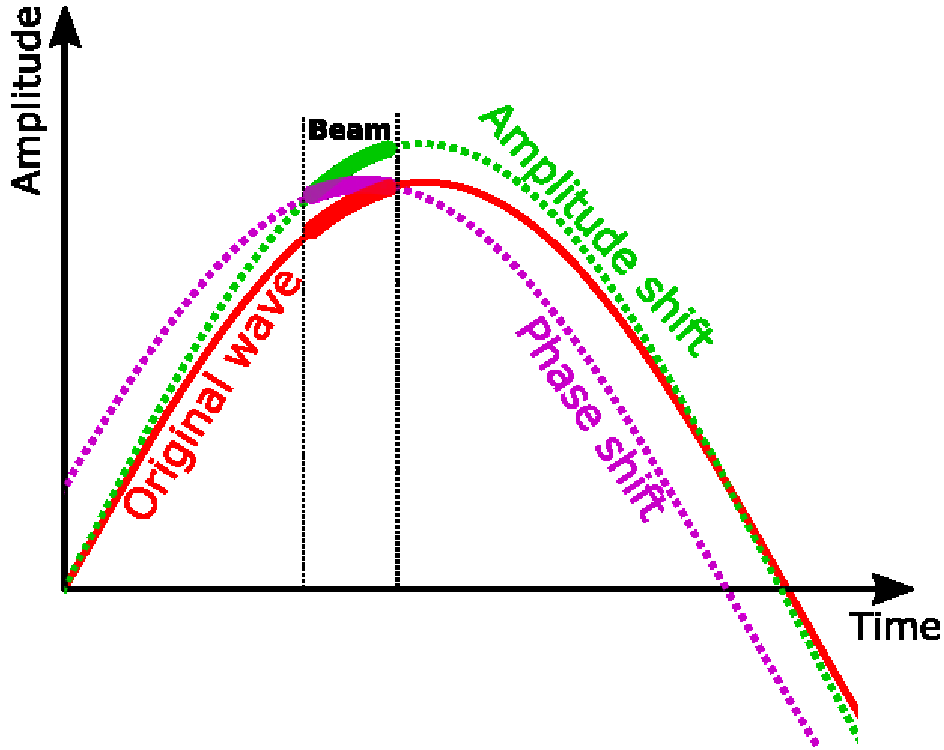
Gun reliability summary

- The RF gun conditioning and run at various RF system setups a **two-window layout** (two RF vacuum windows installed in 5-MW waveguides, an in-vacuum T-combiner, and in-vacuum 10-MW directional coupler) is the most reliable for the *European XFEL* specifications on peak and average power performance.
- Summarizing conditioning history of several gun cavities yields a typical conditioning time of 3 to 4 months.
- Main factors impacting the conditioning are:
  - field emission
  - secondary emission
  - outgassing

Gun Stability

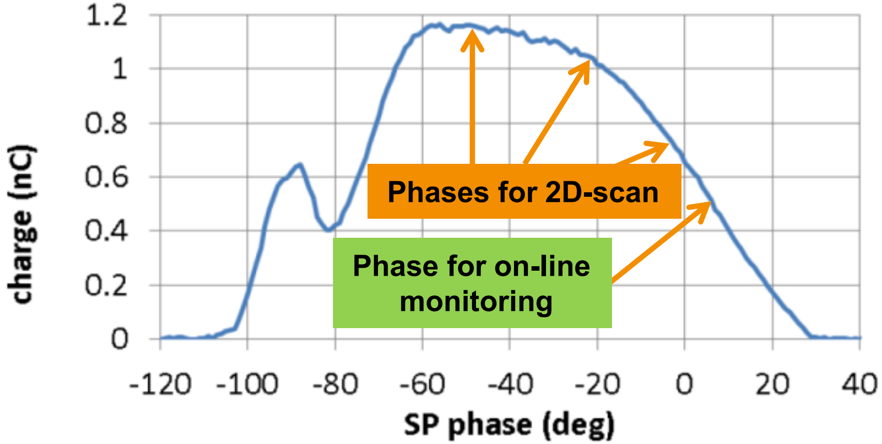
RF Gun stability

- A significant contribution to the arrival time jitter and the longitudinal bunch profile variation is coming from the laser-driven RF gun.
- Several types of jitter can impact the stability of RF gun, but the most substantial influence have fluctuations of the **RF launch phase** and the **cathode laser energy**.

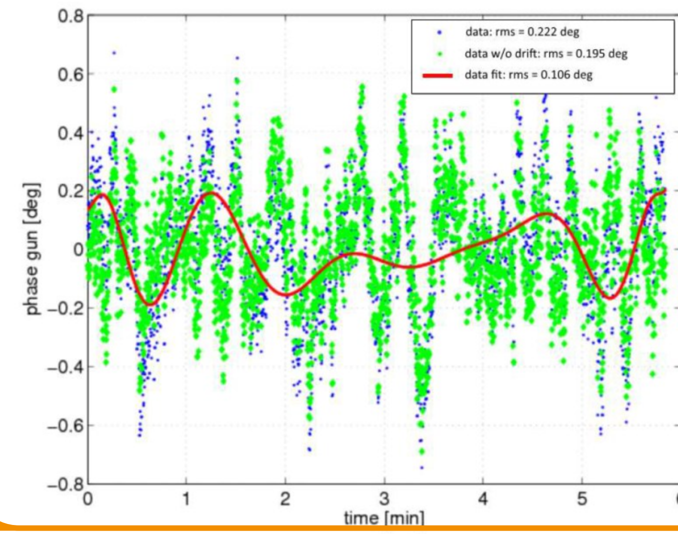


Phase jitter measurement techniques

Charge phase scan for the beam based phase jitter measurements



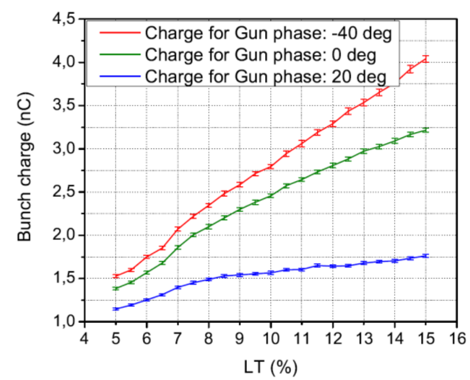
On-line monitoring tool

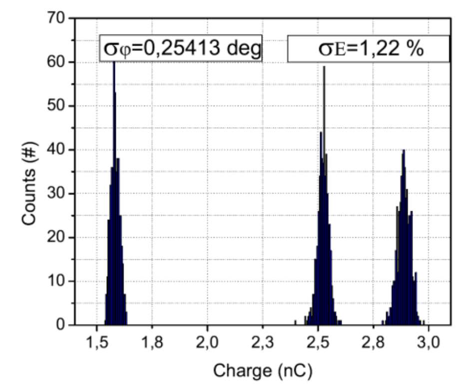


2D phase scan technique

- The distribution function of the RF launch phase and the laser energy can be presented by a **2D Gaussian distribution**.
- The technique utilizes the bunch charge **dependence on** the **gun phase** and **the laser energy**.
- The **main assumption** of the method is an **independence of the jitters** of the RF launch phase and the cathode laser pulse energy.

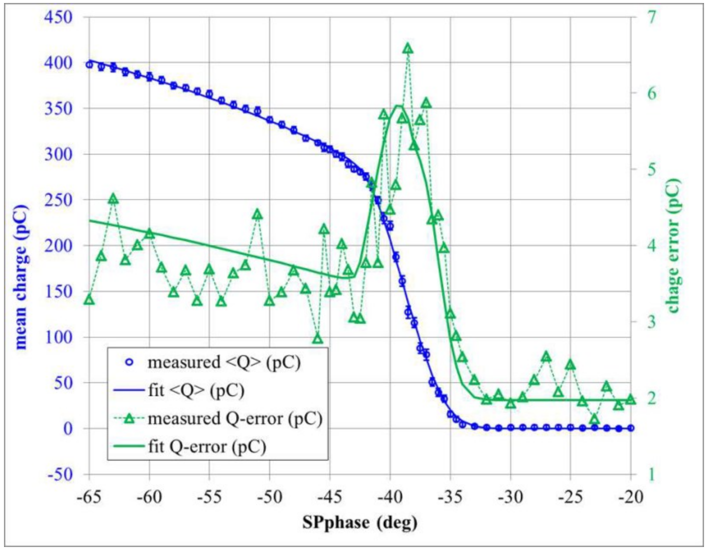
$$P(\phi, E) = \frac{1}{2\pi\sigma_\phi\sigma_E}\exp\left(-\frac{\Delta\phi^2}{2\sigma_\phi^2} - \frac{\Delta E^2}{2\sigma_E^2}\right)$$





Phase jitter measurement techniques

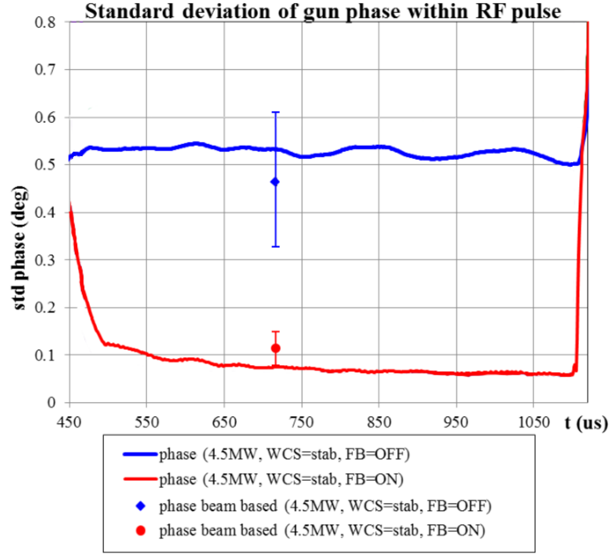
Phase jitter measurement technique utilizing Gaussian beam charge Phase Scan and multidimensional Fit (GaussPSF)

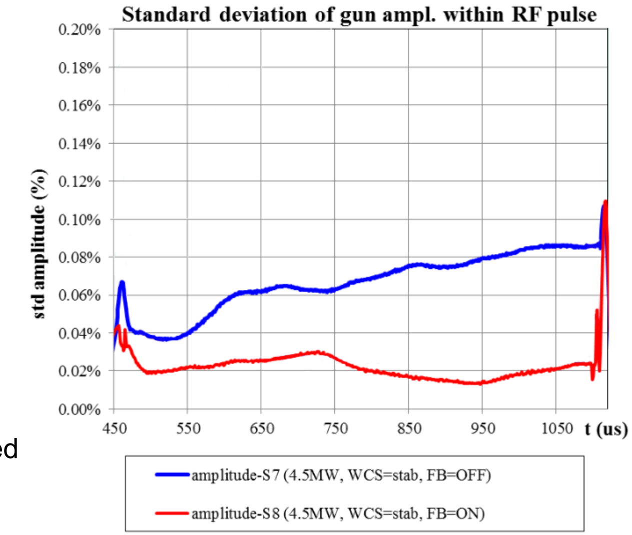


$$Q_{fit}(SPphase) = Q_{bkg} + A \cdot F_{schottky}(\phi) \cdot (1 - Erf\left[C \cdot \phi\right])$$

$$F_{schottky}(\phi) = \begin{cases} \sqrt{1 - S \cdot \sin\frac{\pi\phi}{180}} & \text{if } \phi \leqslant 0 \\ 1 & \text{if } \phi > 0 \end{cases}$$

µTCA LLRF tools for phase measurements

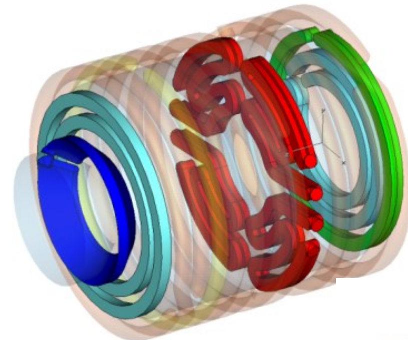


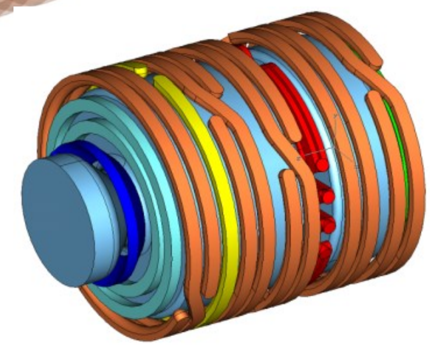


The µTCA LLRF system is developed and maintained by MSK group, DESY Hamburg.

Stabilization systems: Gun water cooling system (WCS)

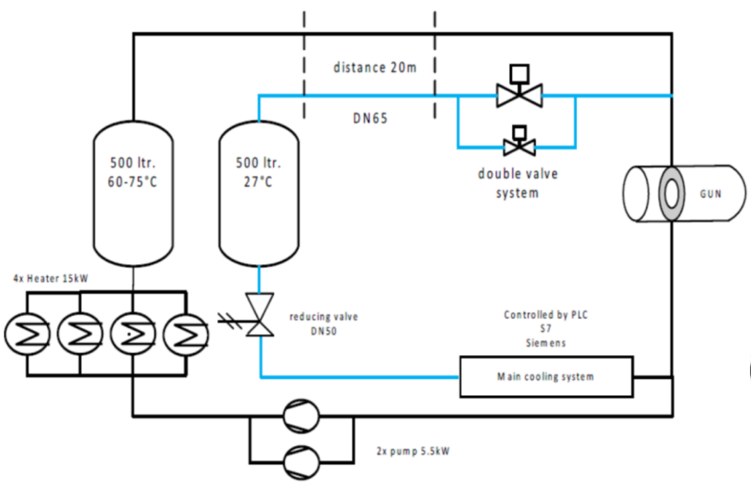
- RF pulse heating restricts peak and average power in resonant cavities like RF guns.
- During the RF pulse, heat propagates from the surface into the cavity body with a sharp temperature front.
- Cooling of the PITZ gun is realized by 14 water cooling channels located in the gun walls.
- The temperature reading is realized by a temperature sensor with high resolution.



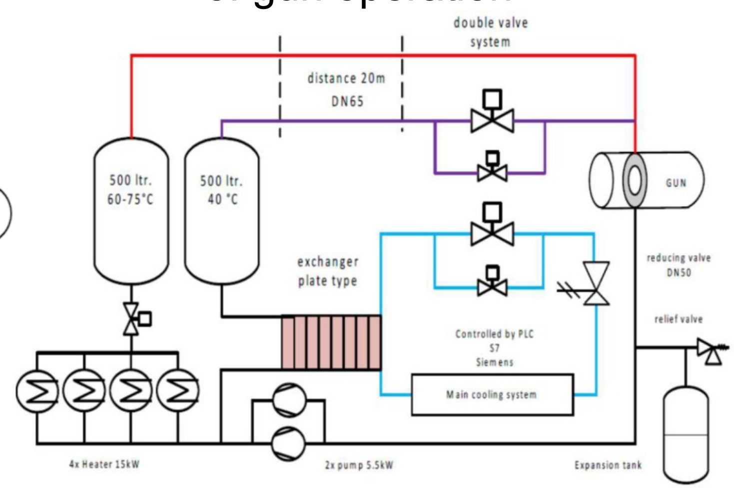


Water cooling channels of the Gun cavity

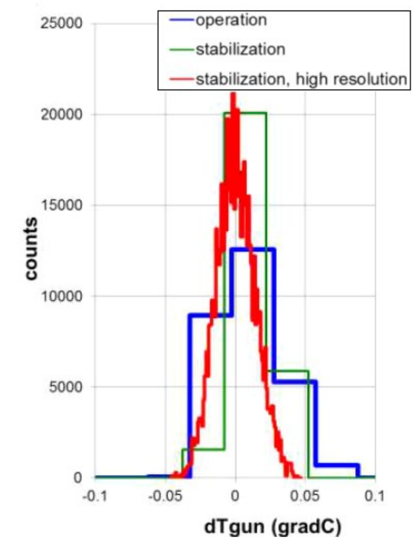
Setup for **start-up** and **stable** modes of gun operation



Setup for **stabilization** mode of gun operation



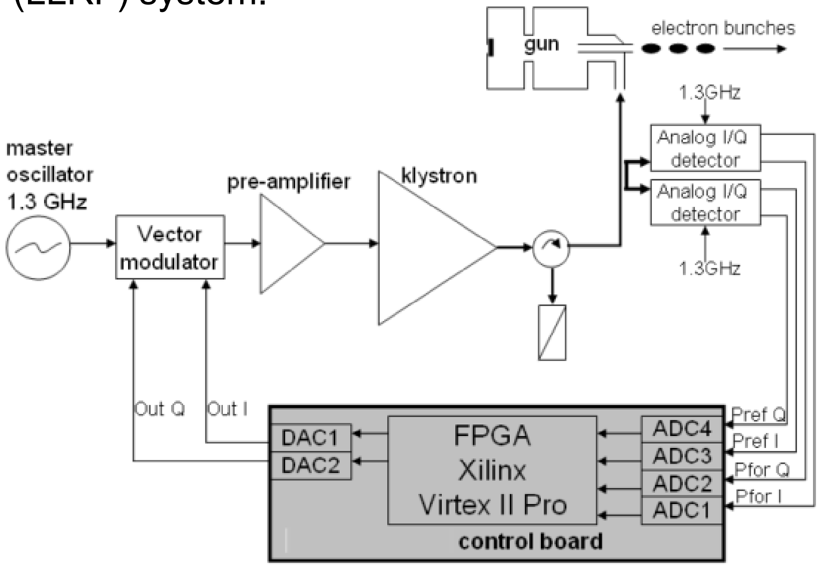
Temperature readings



Stabilization systems: FeedBack (FB) and Pulse Width Modulation (PWM)

RF FeedBack

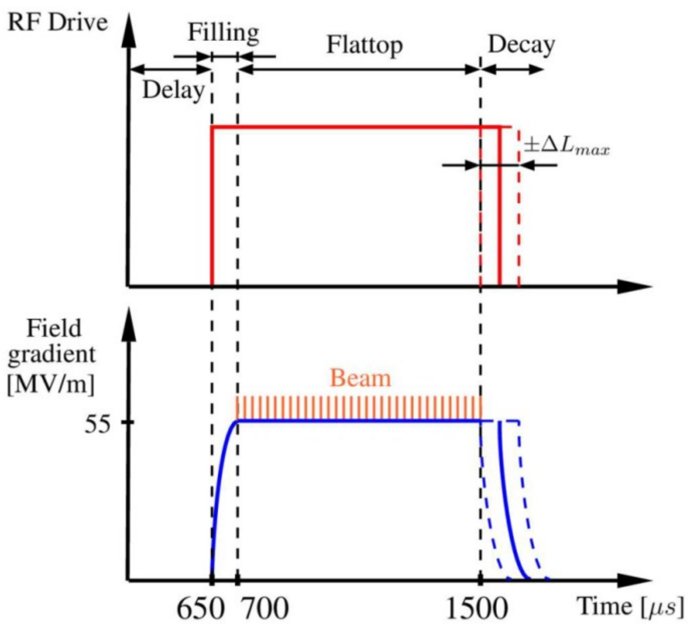
The stabilization of RF amplitude and phase of the gun cavity is organized employing a Low-Level RF (LLRF) system.



The stabilization is **implemented via** measurements of **RF field changes** in the cavity combined with calculation of its errors and comparing with a set point and application of a closed feedback loop to a forward signal.

Pulse Width Modulation

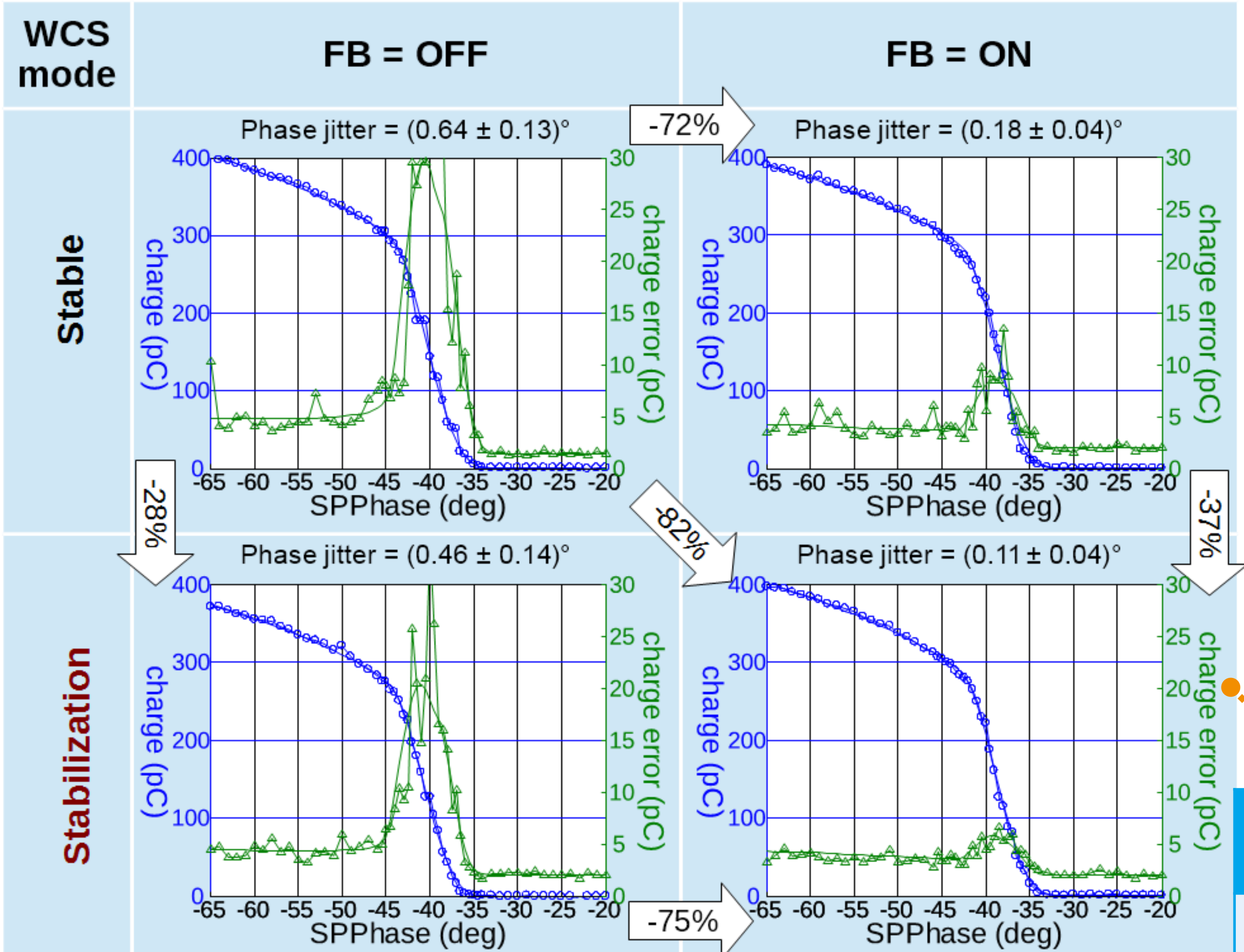
Pulse Width Modulation generates **small RF pulse length variations** within the range of 10μs.



The system requires a **high precision temperature** estimation with small time delay for pulse-to-pulse feedback.

The μTCA LLRF system is developed and maintained by MSK group, DESY Hamburg.

Phase stability measurements results

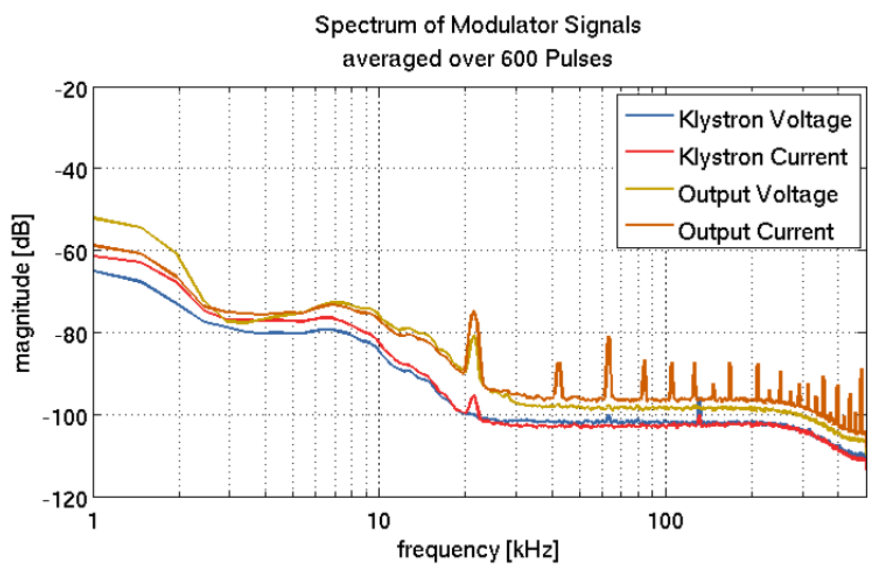


RF gun stability measurements by GaussPSF technique.

	PWM OFF	PWM ON
σ_{temp}, °C	0.02	**0.01**
σ_{phase}, °	0.09	**0.06**
$\sigma_{amplitude}$, %	0.03	**0.02**

Phase stability summary

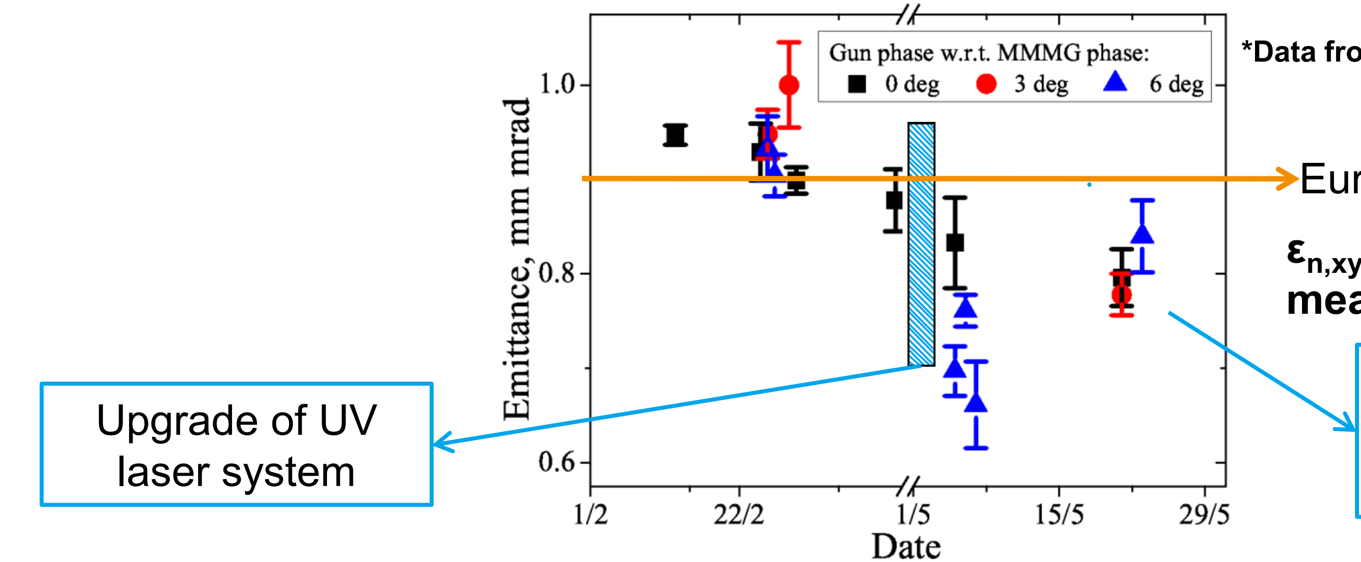
- The systems for the PITZ gun stabilization improve were implemented:
  - pulse width modulation
  - µTCA low-level RF with feedback
  - stabilization mode of the water cooling system with improved readout
- The measured RF amplitude stability of the gun (**0.02%** RMS) is close to the XFEL specifications (**0.01%** RMS).
- The systems helped to **decrease** the RF phase **jitter** by ~**90%**, resulting in **0.06º** RMS. However, it is still higher than the XFEL specifications (**0.01º** RMS phase jitter).
- The limiting factor is the Thomson modulator **20kHz** noise.



Gun Performance

Motivation of the beam asymmetry studies

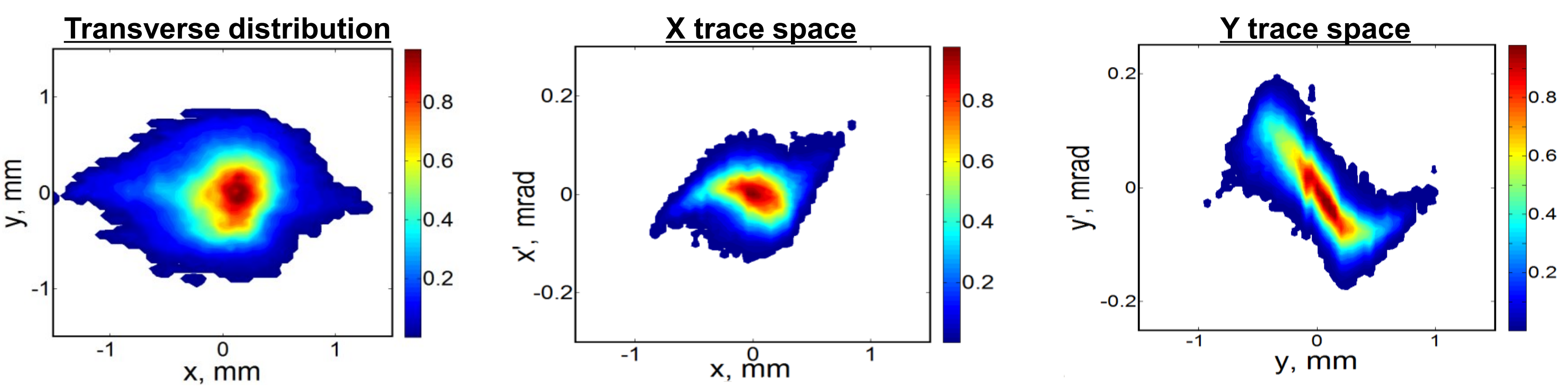
The first and main task of the PITZ facility was the **experimental verification** of the RF photoelectron gun ability to provide a beam with parameters satisfying the XFEL project requirements: projected emittance value smaller than **1mmmrad** for **1nC** bunch charge.



***Data from PhD Thesis of Grygorii Vashchenko**

$\varepsilon_{n,xy}$ < 0.9mmmrad was measured regularly

Azimuthal asymmetry of the electron beam in a rotationally symmetric photoinjector



Motivation of the beam asymmetry studies: why it is bad?

- Emittance coupling:

4D trace space matrix:

$$\widehat{M^T} = \begin{pmatrix} \langle x^2\rangle & \langle xx'\rangle & \langle xy\rangle & \langle xy'\rangle \\ \langle xx'\rangle & \langle x'^2\rangle & \langle x'y\rangle & \langle x'y'\rangle \\ \langle xy\rangle & \langle x'y\rangle & \langle y^2\rangle & \langle yy'\rangle \\ \langle xy'\rangle & \langle x'y'\rangle & \langle yy'\rangle & \langle y'^2\rangle \end{pmatrix}$$

$$\varepsilon^4_{tr,4D} = \det||\widehat{M^T}||$$

$$\varepsilon^4_{tr,4D} = \varepsilon^2_{tr,x}\varepsilon^2_{tr,y} - \text{coupling term}$$

4D trace space matrix in case of no coupling:

$$\widehat{M^T} = \begin{pmatrix} \langle x^2\rangle & \langle xx'\rangle & 0 & 0 \\ \langle xx'\rangle & \langle x'^2\rangle & 0 & 0 \\ 0 & 0 & \langle y^2\rangle & \langle yy'\rangle \\ 0 & 0 & \langle yy'\rangle & \langle y'^2\rangle \end{pmatrix}$$

$$\varepsilon^4_{tr,4D} = \varepsilon^2_{tr,x}\varepsilon^2_{tr,y}$$

$$\varepsilon^2_{tr,x} = \langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2$$

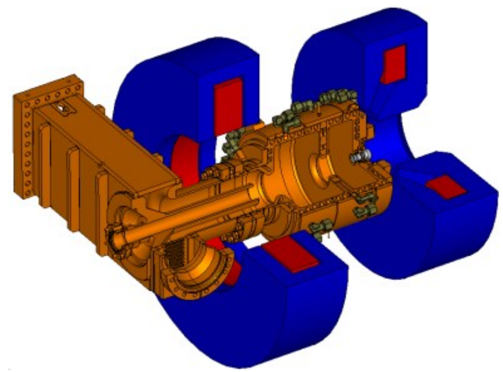
$\varepsilon_{tr,4D}$ is the conserved quantity, coupling term > 0 $\Rightarrow$ growth of $\varepsilon_{tr,x} \cdot \varepsilon_{tr,y}$

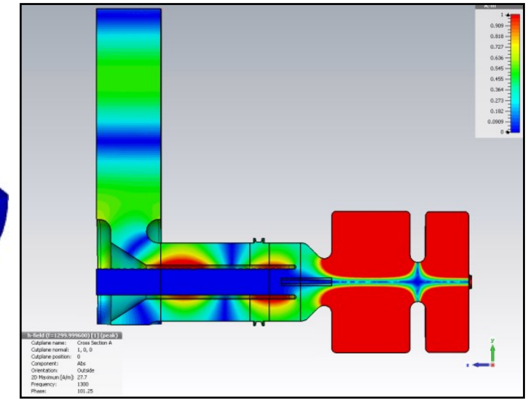
- Chromatic aberration of the beam due to a time-dependent transverse kick.
- Beam optics does not work as designed.

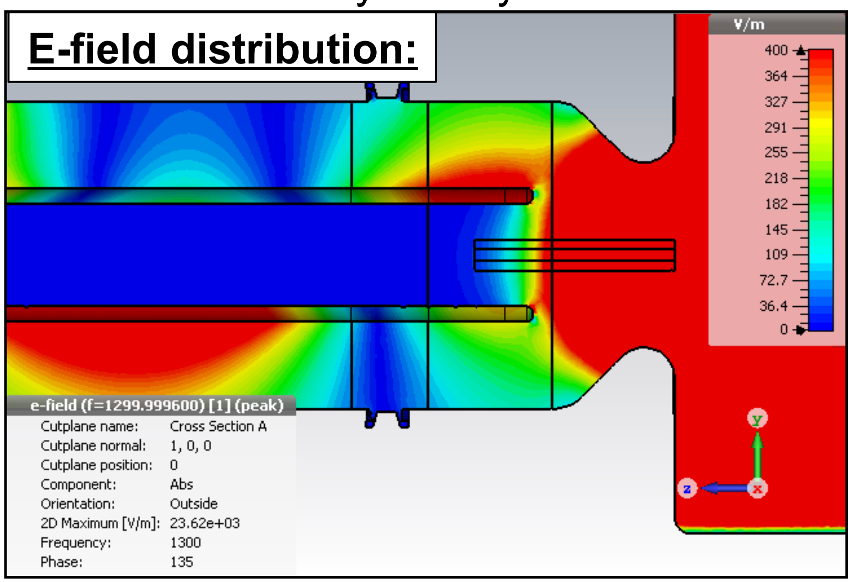
RF Coupler kick simulations

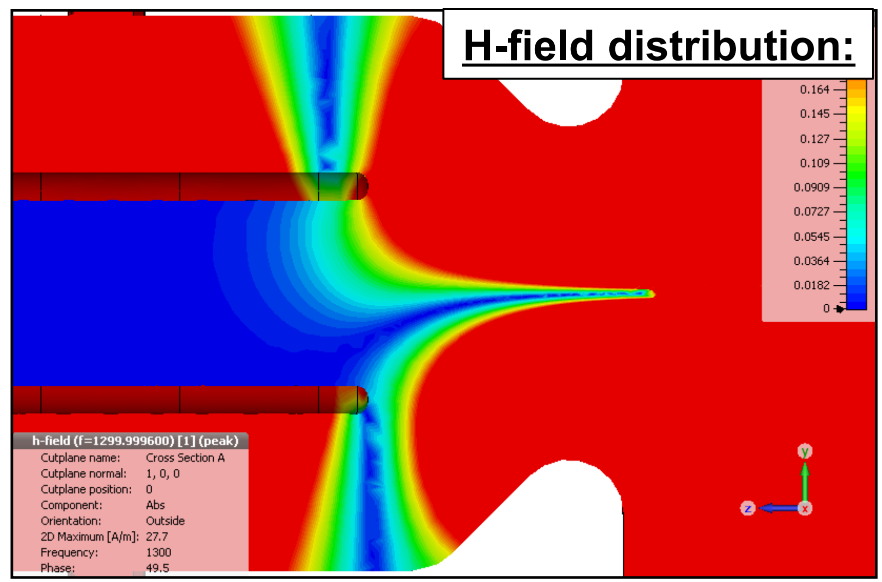
> RF field simulations (CST MWS):

- The full model of the gun:
  - the gun cavity
  - the coupler
  - simplified cathode
- Frequency domain solver (F-solver)
- Tetrahedral mesh (~10^6 elements) with 2^{nd} order curved elements
- Half structure symmetry









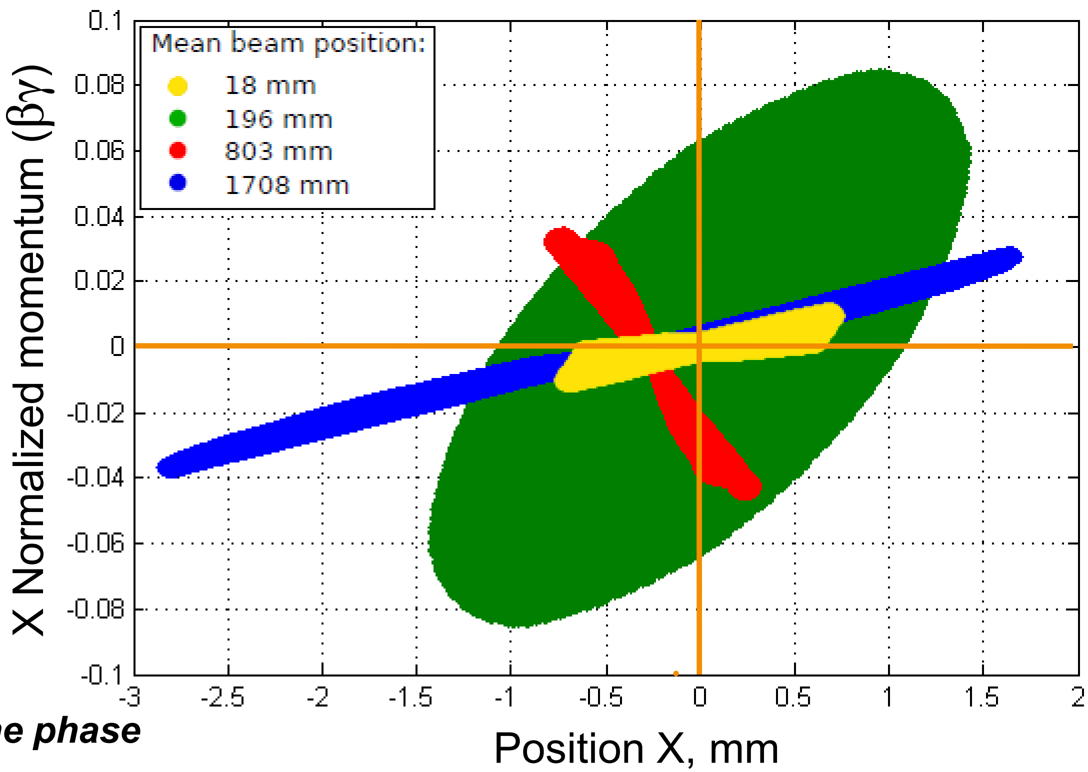
Particle tracking in CST particle studio: PIC solver

- Particle-in-cell solver
- Hexahedral mesh
- Imported fields for the limited volume
- Particle source parameters:
  - 0.6mm radius
  - 22ps flattop pulse length
  - 1nC bunch charge

Time, ps	Z mean position, mm	X mean position, mm
100.1	18 (1st cell)	0
700.2	196 (RF coupler region)	-0.006
2730.1	803 (LOW.Scr1)	-0.251
5760.1	1708 (LOW.Scr3)	-0.589

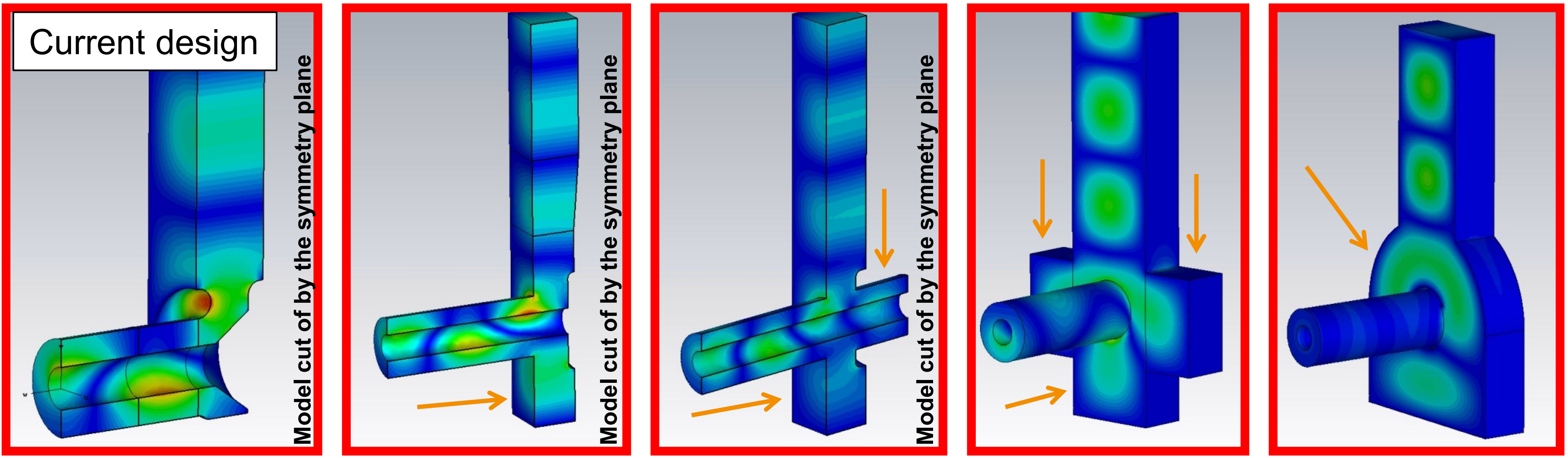
x kick angle: k_x = -0.31mrad

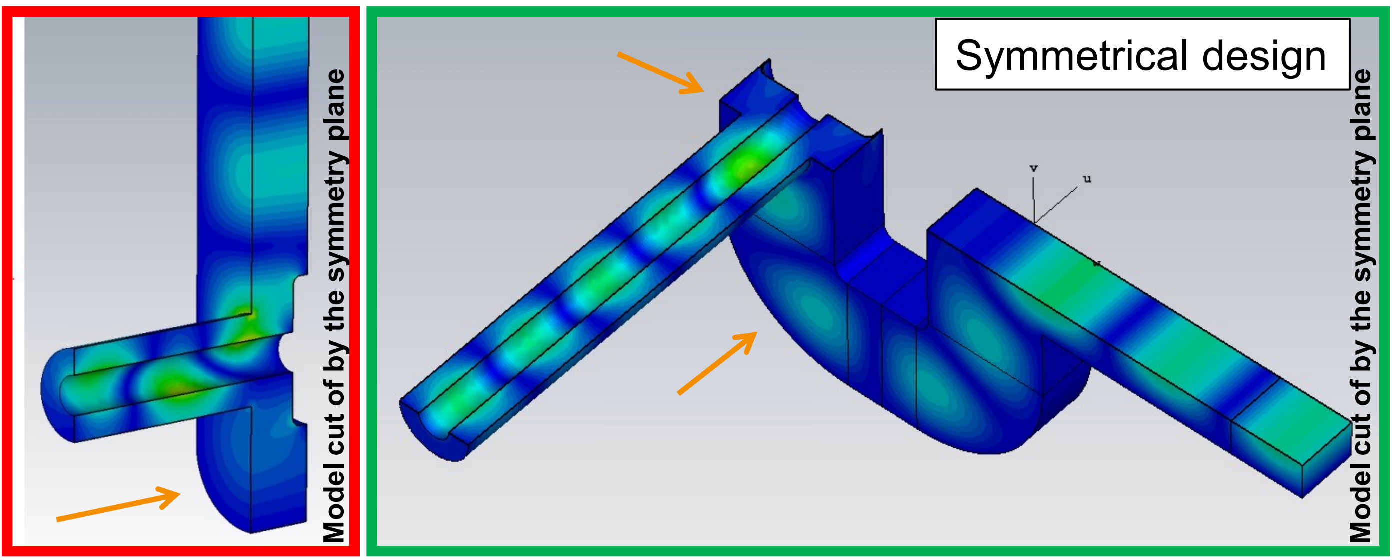
y kick angle: k_y = 0.37mrad



Detailed studies of the kick impact onto the phase space (emittance) are ongoing.

Another models of coupler

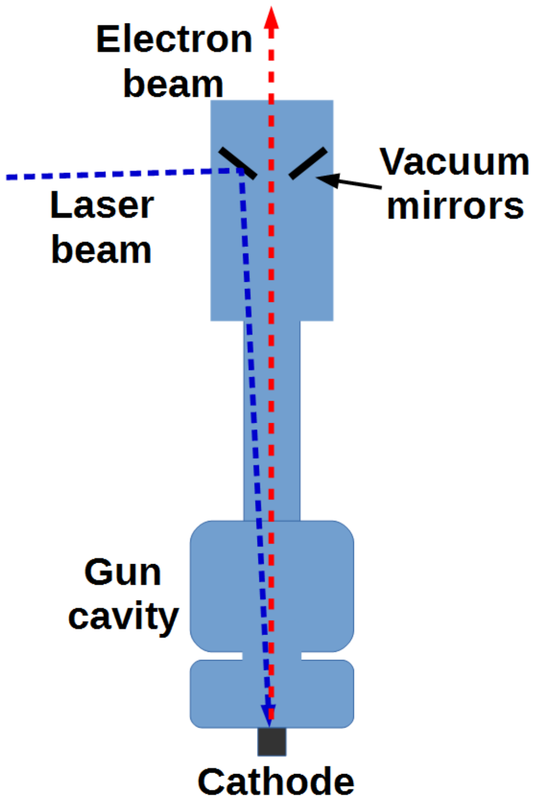




Only symmetrical design of an RF coupler can provide symmetrical fields at the gun cavity input.

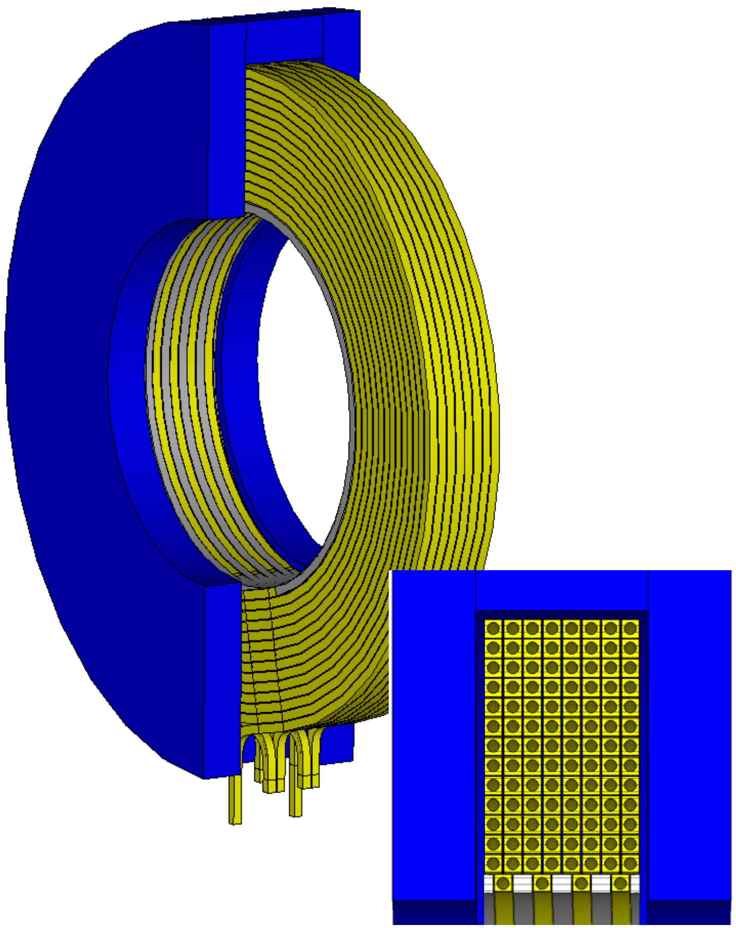
Other possible origins of e-beam asymmetry

Vacuum mirror



No difference found between default (1 mirror) and symmetric (2 mirrors) setups

Solenoid imperfections

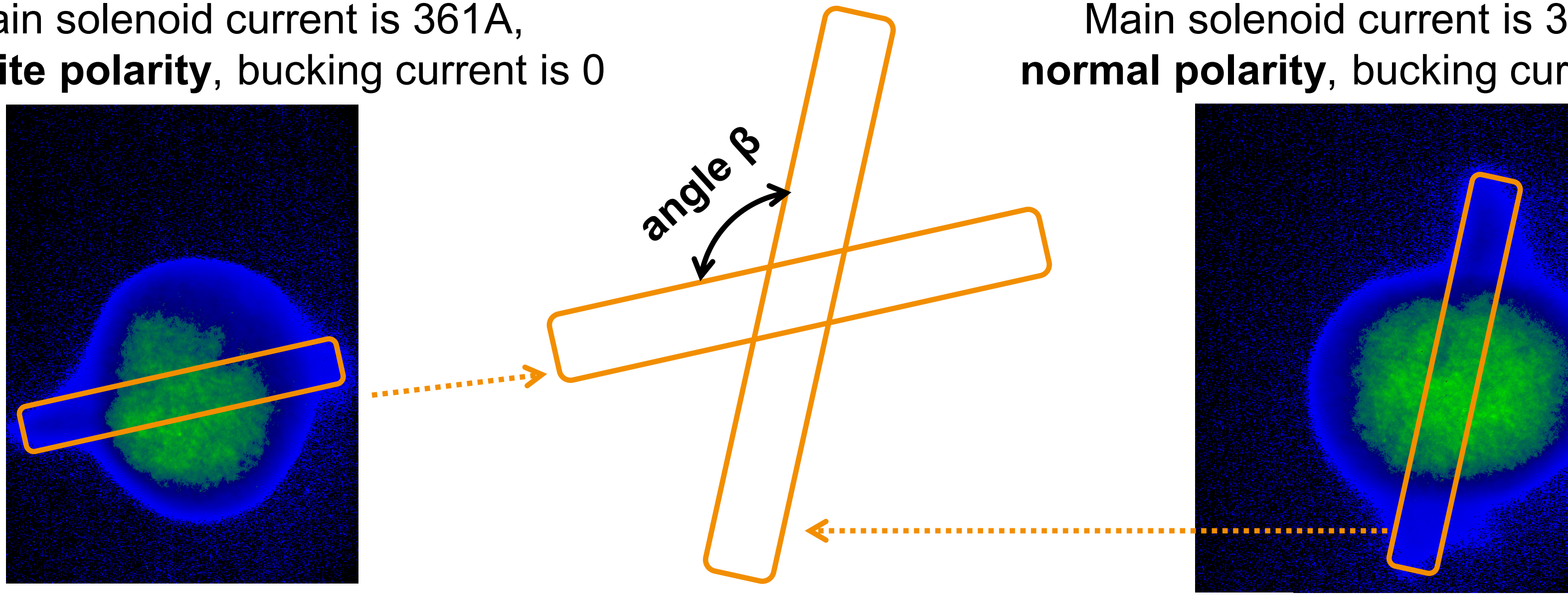


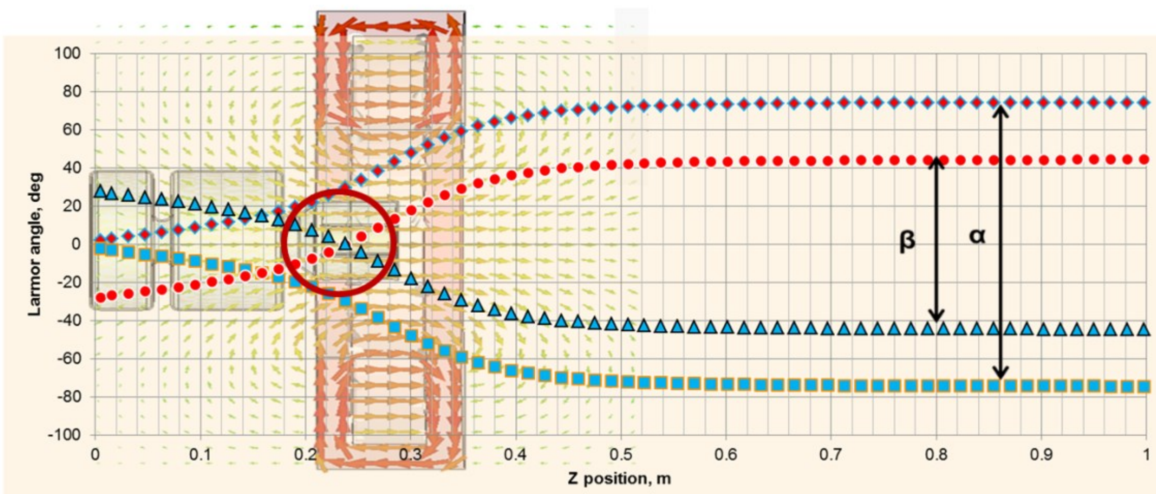
Larmor angle experiment

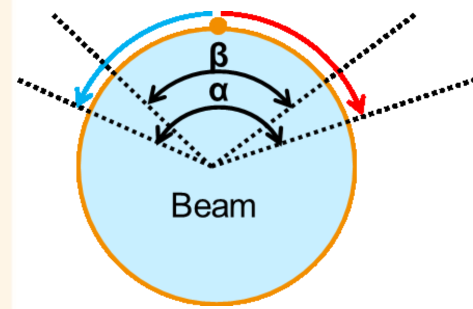
Beam at the 1st screen after the booster

Main solenoid current is 361A, **opposite polarity**, bucking current is 0

Main solenoid current is 361A, **normal polarity**, bucking current is 0







Outcome of beam imperfections studies

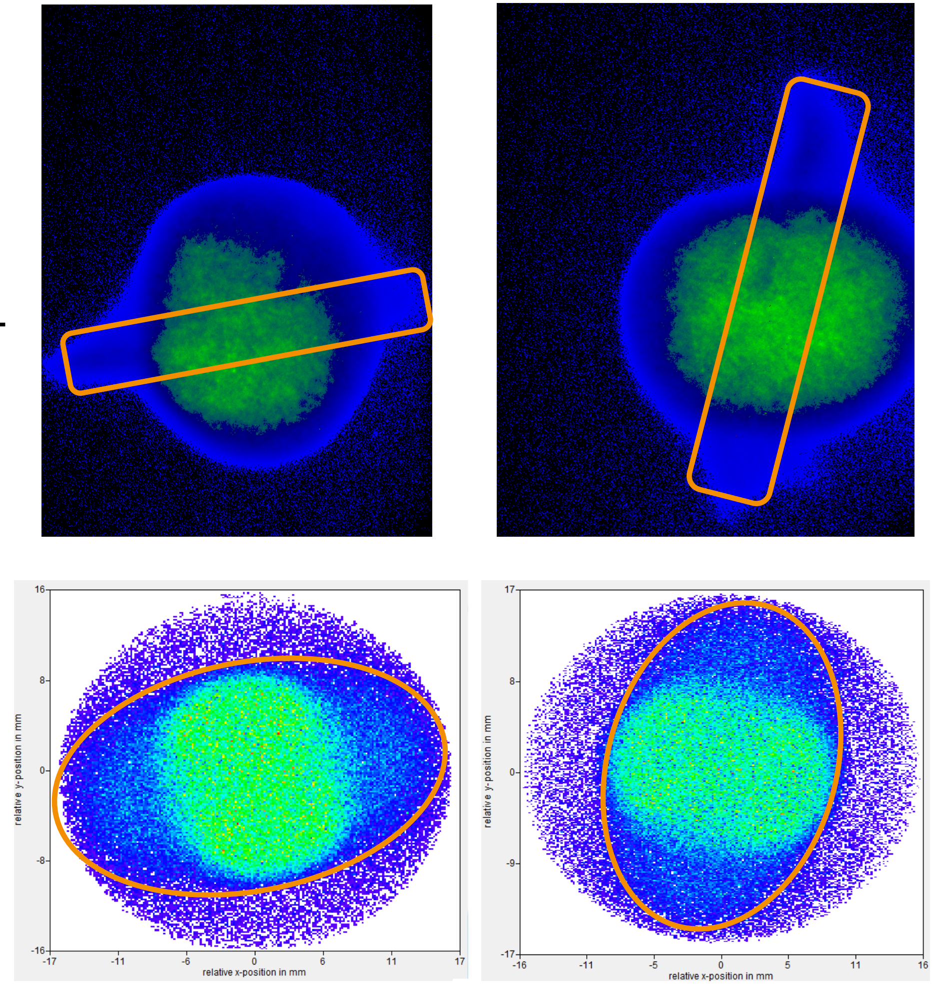
Simulations with rotation quads model

The simulations performed by Q.Zhao.

I main = -361A   I main = +361A

Experiment

Simulations



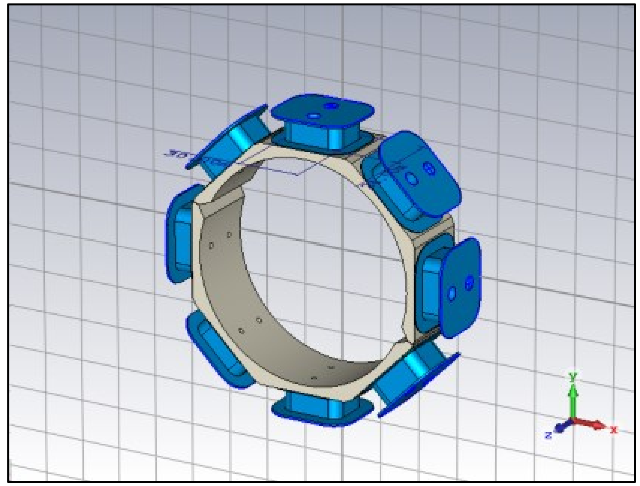
<u>Summary of the simulations:</u>

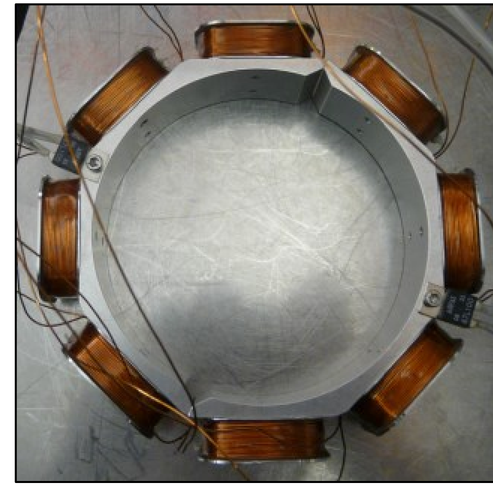
- Position: z = 0.18m (coaxial transition to the full cell of the gun)
  - Quad orientation: **Skew quad**
  - Quad polarity is **not changed** with the main solenoid polarity variation
- Position: z = 0.36m (far side of the main solenoid)
  - Quad orientation: **Normal quad**
  - Quad polarity is **changed** with the main solenoid polarity variation

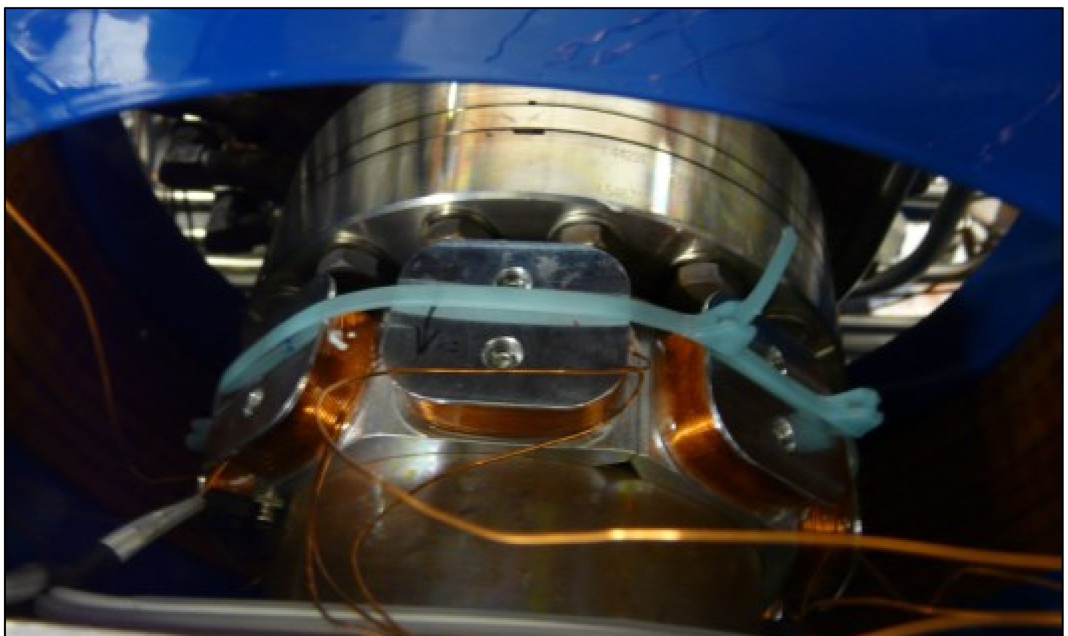
Current design of the Gun Quadrupoles (8 coils)

Parameters:

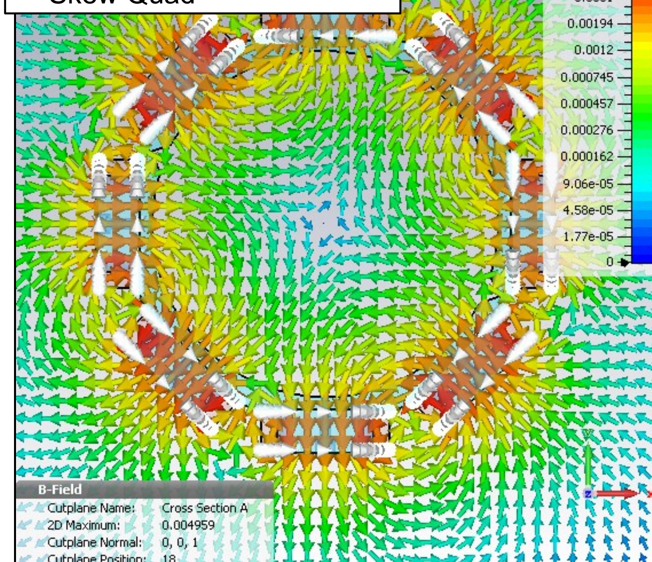
- Combination of a **normal** and a **skew** quads
- **Aluminum** frame
- 0.56 mm copper cable
- 140 windings per coil
- 2 thermal switchers (80º C max)
- Non-magnetic screws
- Quad gradient = 0.0117T/m @ 1A







$I_{\text{Normal Quad}} = -0.6A$
$I_{\text{Skew Quad}} = -0.5A$

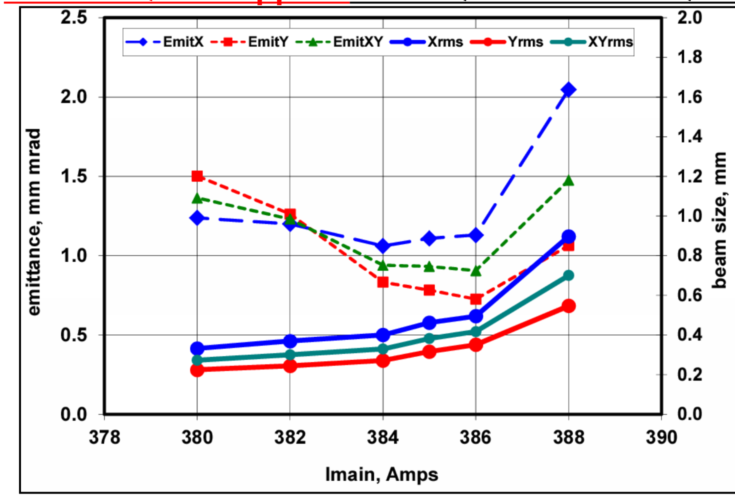


Gun quads influence on emittance

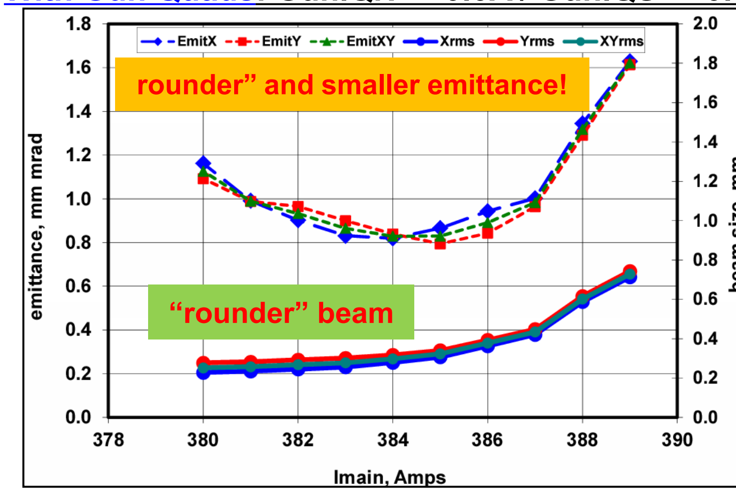
Machine parameters:

- BSA = 1.2mm
- Charge = 500pC
- Gun power = 6.5MW
- Booster power = 3MW
- Gaussian Laser temporal profile: ~11.5ps
- Bunch length (TDS) = 15.8ps
- The gun quad currents were selected to deliver the most round beam spot at High1Scr1 and High1Scr4 simultaneously

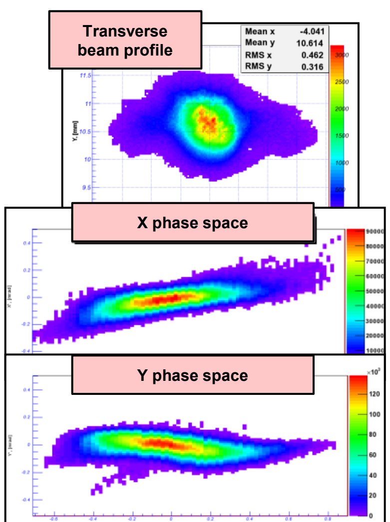
No Gun Quads applied: Gun QN = 0A / Gun.QS = 0A



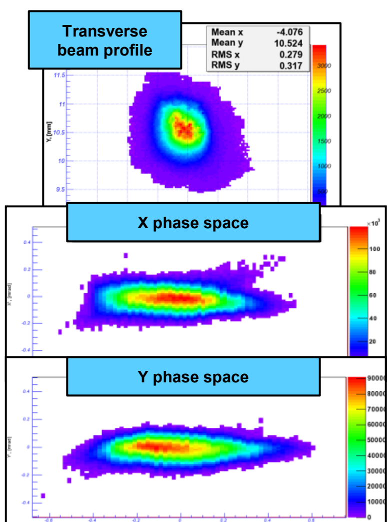
With Gun Quads: Gun.QN = -0.6A / Gun.QS = -0.5A



No Gun Quads



With Gun Quads



	No Gun Quads			With Gun Quads		
	x	y	xy	x	y	xy
Emittance, mmmrad	1.11	0.78	0.93	0.82	0.84	0.83
Beam RMS size, mm	0.46	0.32		0.28	0.32	
α	-0.99	0.39		0.06	-0.01	
β	4.85	4.37		3.18	3.24	
γ	0.41	0.26		0.32	0.31	

Beam asymmetry studies: Summary and Outlook

Photoelectron **beam asymmetry** observed in a **rotationally symmetric** photoinjector

- the beam asymmetry location was found around **0.2m** and **0.4m** downstream the cathode
- the most probable **reasons** are **RF coupler** or/and **the main solenoid field** asymmetries

> The compensating quads were produced and implemented

- the gun quads are able to partially compensate beam transverse asymmetry
- the beam emittance (horizontal and vertical phase spaces) becomes symmetric

> A copy of the gun quads is installed at European XFEL and prepared for FLASH

> Further studies are ongoing:

- quantitative characterization of the beam asymmetry sources
- studies on the main solenoid field asymmetry

Stability and performance studies of the PITZ photoelectron gun: Summary

Reliable and **stable** run of high **brightness** photo injector is a key issue for successful operation of modern SASE FELs (like European XFEL and FLASH).

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

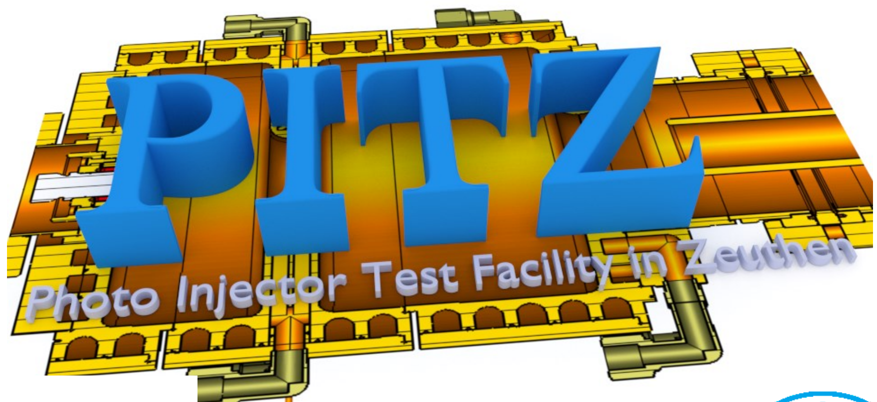
→ demonstration of required **performance**.

	Results of this work
Reliability	• Development of **LILI** tool for detailed interlock investigations → classification of each gun IL • Analysis and Elucidation of the PITZ experience on high brightness RF guns conditioning and operation → two-window RF feed layout works • Characterization and Evaluation of crucial **factors limiting** injector operation (dark current and MP discharge) • Summarization of IL structure and Distillation of the gun **conditioning procedure** at PITZ
Stability	• Elaboration of tools for RF gun stability **monitoring** and **analysis** (μTCA and beam-based) • Analysis of PITZ gun **phase** and **amplitude** stability for various options of the WCS and LLRF → quantification of factors improving stability
Performance	• Studies on electron beam **asymmetry** → kicks onto the transverse phase space from the RF coupler and main solenoid imperfections • Alternative **designs** of **RF coupler** have been studied • Based on these studies **gun quadrupole coils** are developed and applied at relevant photo injectors to compensate the asymmetry kicks

My sincerest gratitude is addressed to:

Prof. Dr. Jörg Roßbach, Dr. Frank Stephan, Dr. Mikhail Krasilnikov, Dr. G. Vashchenko, Dr. A. Oppelt, Dr. M. Groß, Dr. H. Qian, Dr. Y. Chen, Dr. Q. Zhao, Dr. M. Otevrel, Dr. G. Asova, Dr. Y. Renier, Dr. B. Marchetti, Dr. S. Rimjaem, Dr. D. Richter, Dr. H. Huck, Dr. X. Li, J. D. Good, G. Loisch, P. Boonpornprasert, Dr. D. Malyutin, Dr. Y. Ivanisenko, Dr. G. Kourkafas, R. Niemczyk, Dr. G. Trowitzsch, B. Petrosyan, Dr. D. Kalantaryan, M. Pohl, G.Koss, Dr. F. Brinker, Dr. S. Schreiber, Dr. D. Kostin and A. Wilhelm.

Thank You for your attention!



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