Photoelectron beam asymmetry studies at PITZ.

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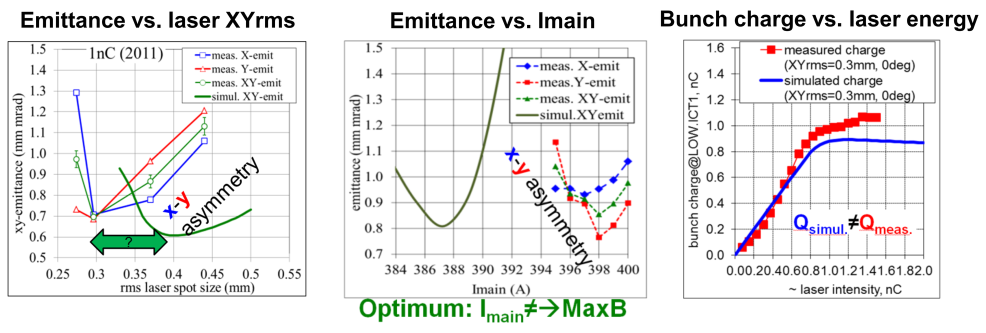
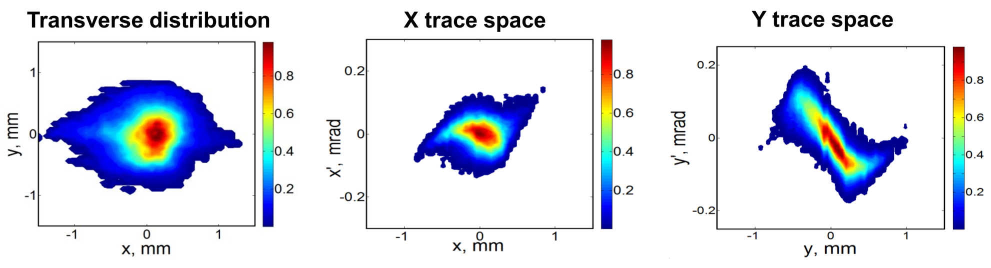
Motivation

The PITZ facility experience with the RF photoelectron gun operation revealed a few problems which have no explanations:

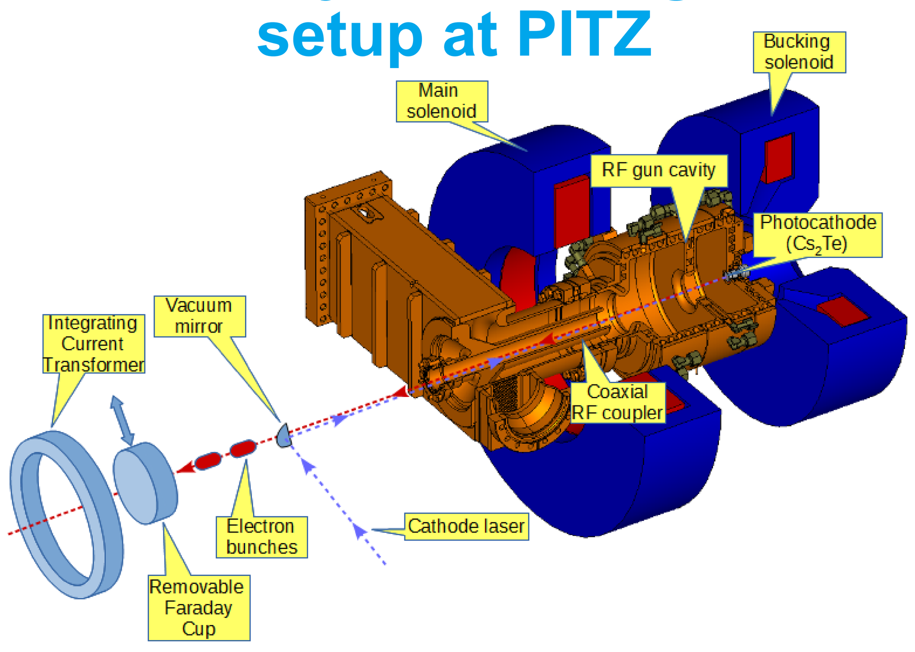
Optimum machine parameters: experiment ≠ simulations



Azimuthal asymmetry of the electron beam in a rotationally symmetric photoinjector



The layout of the gun setup at PITZ

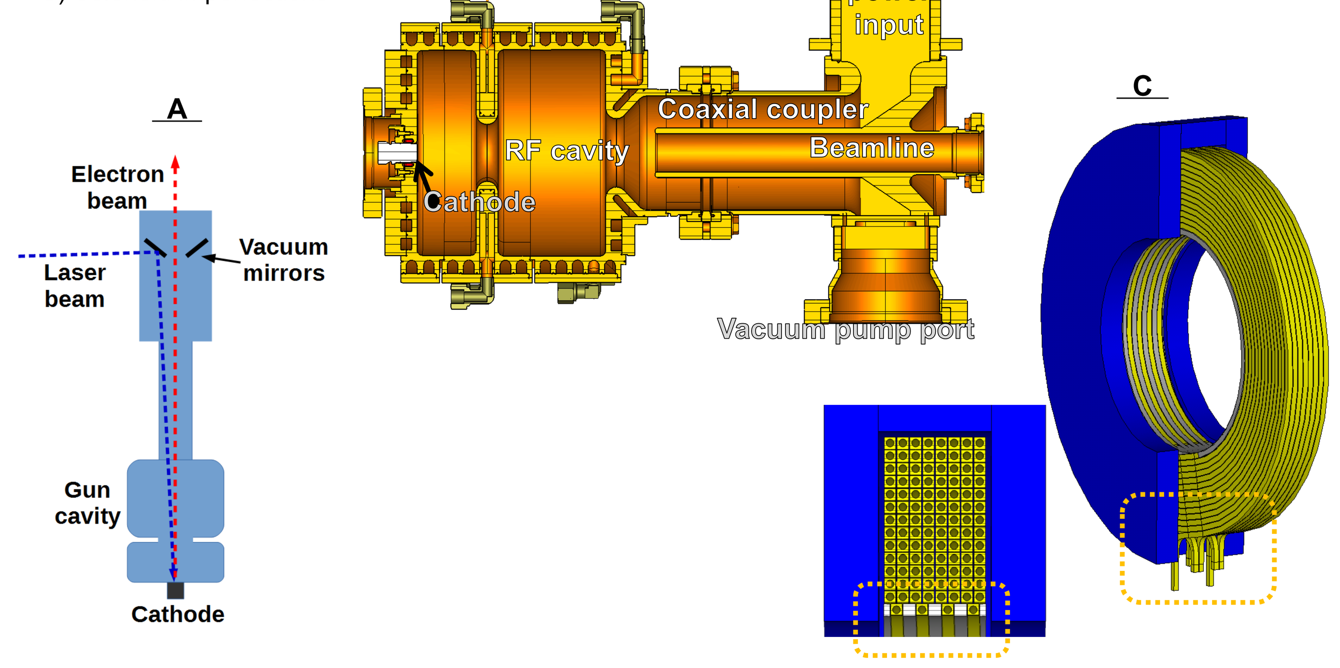


The RF gun cavity is a 1½-cell normal conducting copper cavity, operated at a resonance frequency of 1.3 GHz with a peak power of up to ~7 MW. The cavity has rotationally symmetric design. The RF power to the gun is supplied by a 10 MW multibeam klystron through two equal output ports. In front of the gun the RF pulses from both waveguides are combined using a custom T-shape combiner.

Possible origins of e-beam asymmetry

There are a few possible sources of the beam asymmetry:

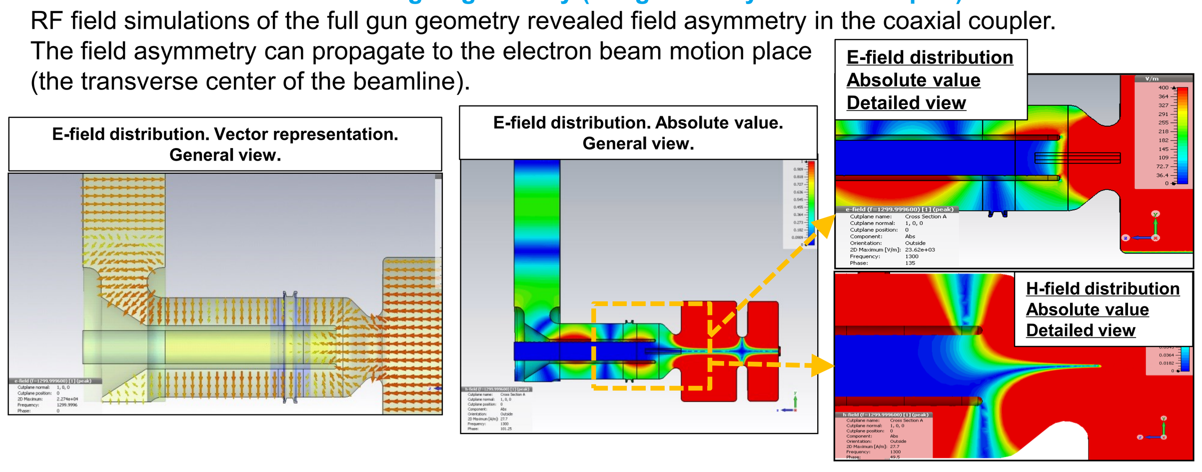
> A) Vacuum mirror (no difference found between default (1 mirror) and symmetric (2 mirrors) setups)
> B) RF coupler field asymmetry
> C) Solenoid imperfections



Electromagnetic fields and particle tracking simulations

RF field simulations for the full gun geometry (the gun cavity with RF coupler)

RF field simulations of the full gun geometry revealed field asymmetry in the coaxial coupler. The field asymmetry can propagate to the electron beam motion place (the transverse center of the beamline).

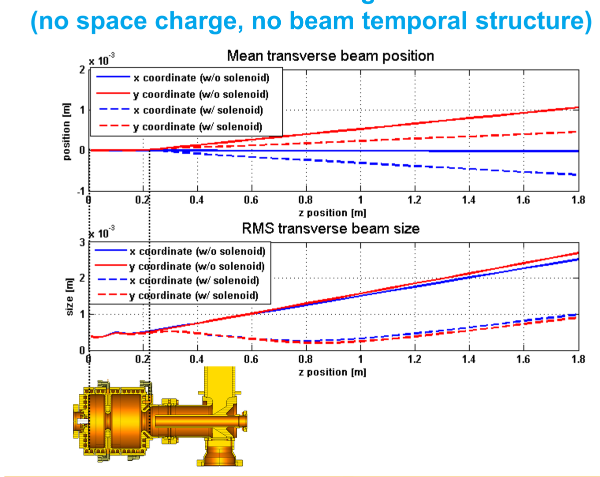


The kick origin is: *asymmetric transition* for WR650 to coaxial waveguide. Too *short* coaxial *antenna*.

Particle tracking simulations

Particle tracking simulations showed that the RF filed asymmetry has an influence on the electron beam dynamics.

CST PS: Tracking solver (no space charge, no beam temporal structure)

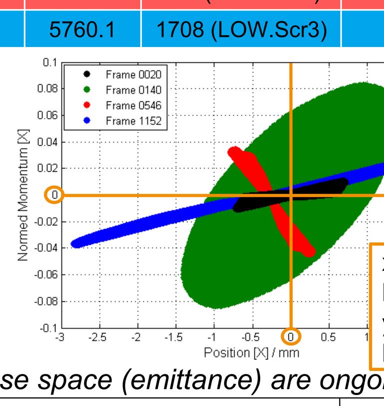


x kick angle:
w/o solenoid: k_x = -0.01 mrad
w/ solenoid: k_y = -0.38 mrad

y kick angle:
w/o solenoid: k_x = 0.66 mrad
w/ solenoid: k_y = 0.27 mrad

CST PS: PIC solver (with space charge, with beam temporal structure)

Frame	Time, ps	Z mean position, mm	X mean position, mm
0020	100.1	18 (1st cell)	0
0140	700.2	196 (RF coupler region)	-0.006
0546	2730.1	803 (LOW.Scr1)	-0.251
1152	5760.1	1708 (LOW.Scr3)	-0.589

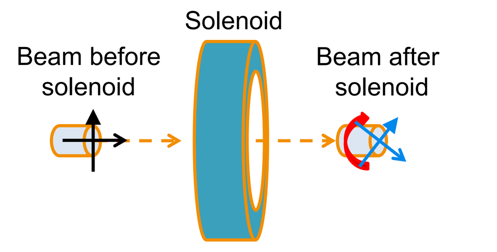


x kick angle:
k_x = 0.31 mrad
y kick angle:
k_y = 0.37 mrad

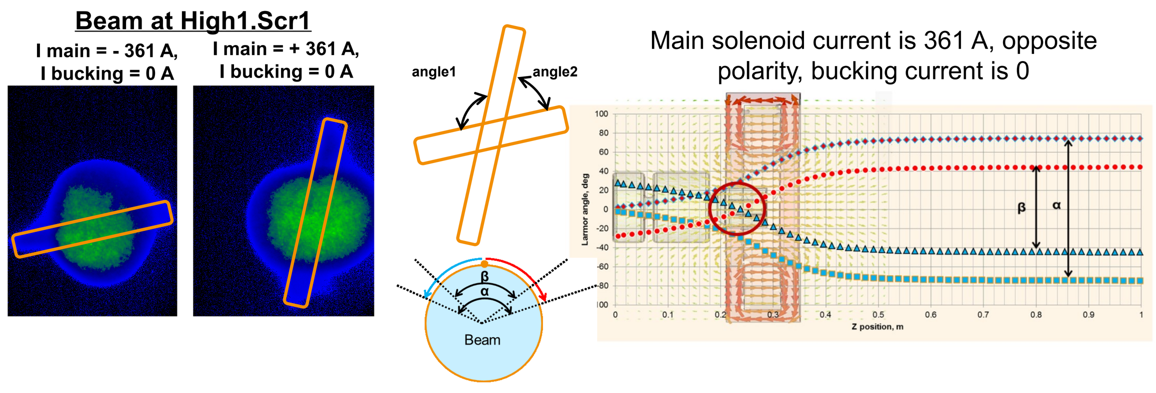
Detailed studies of the kick impact onto the phase space (emittance) are ongoing.

Beam asymmetry modeling by a rotational quadrupole

Larmor angle experiment

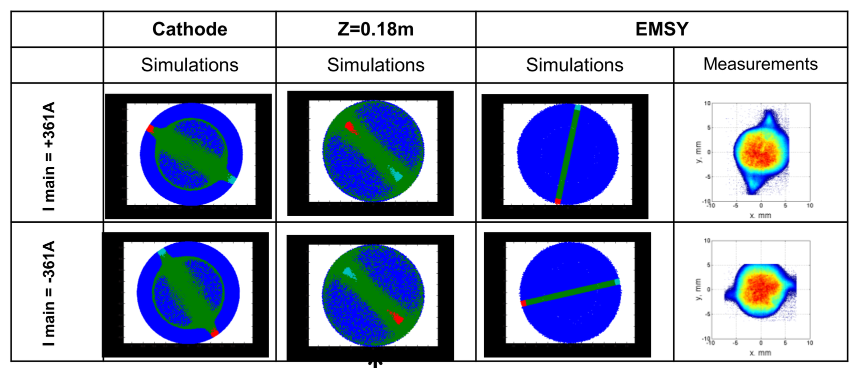


The installation of the main solenoid polarity switcher allowed to perform an experiment on the beam rotation in the solenoid fields (Larmor angle experiment). The Larmor angle experiment revealed the Z position of the electron beam asymmetry source.



"Tracking back" towards cathode (M.Krasilnikov)

The simulations on the "tracking back" of the beam asymmetry features proved that the origin of the beam asymmetry located around 0.2 m downstream the cathode. Moreover, the beam asymmetry source seems has a quadrupole structure. Therefore it can be modeled by a quadrupole.



The kick at z=0.18m is oriented by 45°.

Could it be described by a skew quadrupole?

Measurements (29.09.2015M-A):
- P_{gun}=5MW (6.1MeV/c max)
- Launch phase: MMMG
- Cathode laser:
  - Gaussian 11.5 ps FWHM (expected)
  - BSA=1.2mm (VC2)
- Charge 0.5 nC

Modeling by a rotational quadrupole (Q. Zhao)

Main idea:

1. the kick optics can be **modeled as a rotated quadrupole** with focal length and rotation angle given in terms of the (complex) Voltage kicks.
2. a rotated quadrupole near the coupler is effective at compensating for the kick, cancelling both the coupler emittance and the astigmatic focusing.

Simulations: with assumed skew quadrupoles fields at z= 0.18m. Based on other beam asymmetry studies (Larmor angle experiment).

➔All ASTRA simulation set up are same with experiment set up, beam momentum and solenoid current.

#1 David Dowell, Analysis and Cancellation of RF Coupler- induced Emittance Due to Astigmatism. LCLS-2 TN-15-05 3/23/2015.
#2 John Schmerge, LCLS Gun Solenoid Design Considerations. SLAC-TN-10-084.

$$\tilde{\theta}_q(\phi_s) = \frac{1}{2}\tan^{-1}\frac{v_{xy}^r\cos\phi_s - v_{xy}^i\sin\phi_s}{v_{xx}^r\cos\phi_s - v_{xx}^i\sin\phi_s}$$

$$\frac{1}{\tilde{f}_{q(\phi_s)}} = \frac{eV_{acc}}{\beta\gamma mc^2}\sqrt{\left(v_{xx}^r\cos\phi_s - v_{xx}^i\sin\phi_s\right)^2 + \left(v_{xy}^r\cos\phi_s - v_{xy}^i\sin\phi_s\right)^2}$$

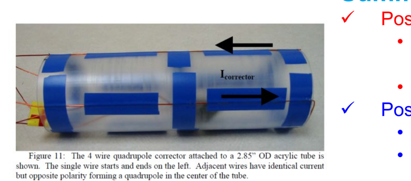


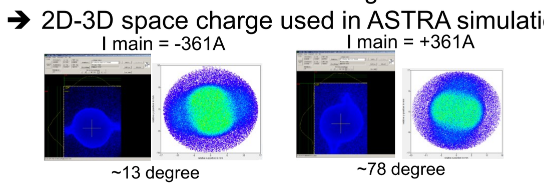
Figure 11: The 4 wire quadrupole corrector attached to a 2.85" OD acrylic tube is shown. The single wire starts and ends on the left. Adjacent wires have identical current but opposite polarity forming a quadrupole in the center of the tube.

Strategy:

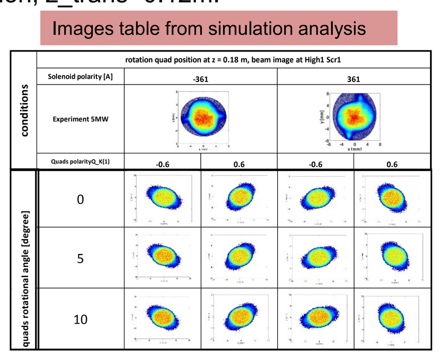
Use rotation quads model in ASTRA simulation by scanning the rotation angle and z position.

➔ Find the parameters for beam images at High1.Scr1 to fit the experiment images, the direction of the beam wings for both solenoid polarity.

➔ 2D-3D space charge used in ASTRA simulation, z_trans=0.12m.



Images table from simulation analysis



Summary of the simulations:

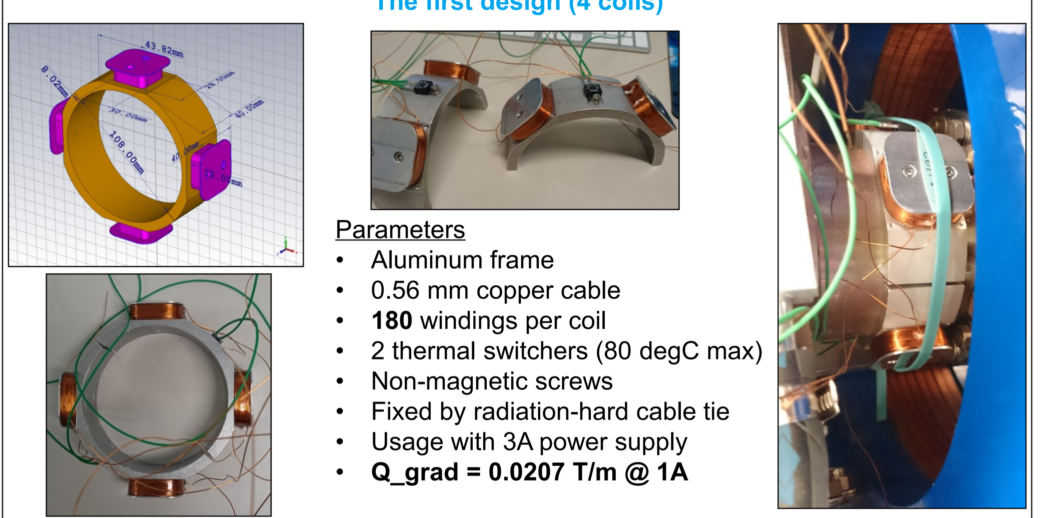
✓ Position: around **z=0.18m.**
- Rotation angle: **Skew quads**: 45 degree (negative polarity) / 135 degree(positive polarity).
- Polarity: same, not effected by solenoid field polarity.

✓ Position: around **z=0.34m**
- Rotation angle: **Normal quads.**
- Polarity: when change the solenoid polarity, the quads polarity also changed.

Design of compensating quadrupoles for the gun

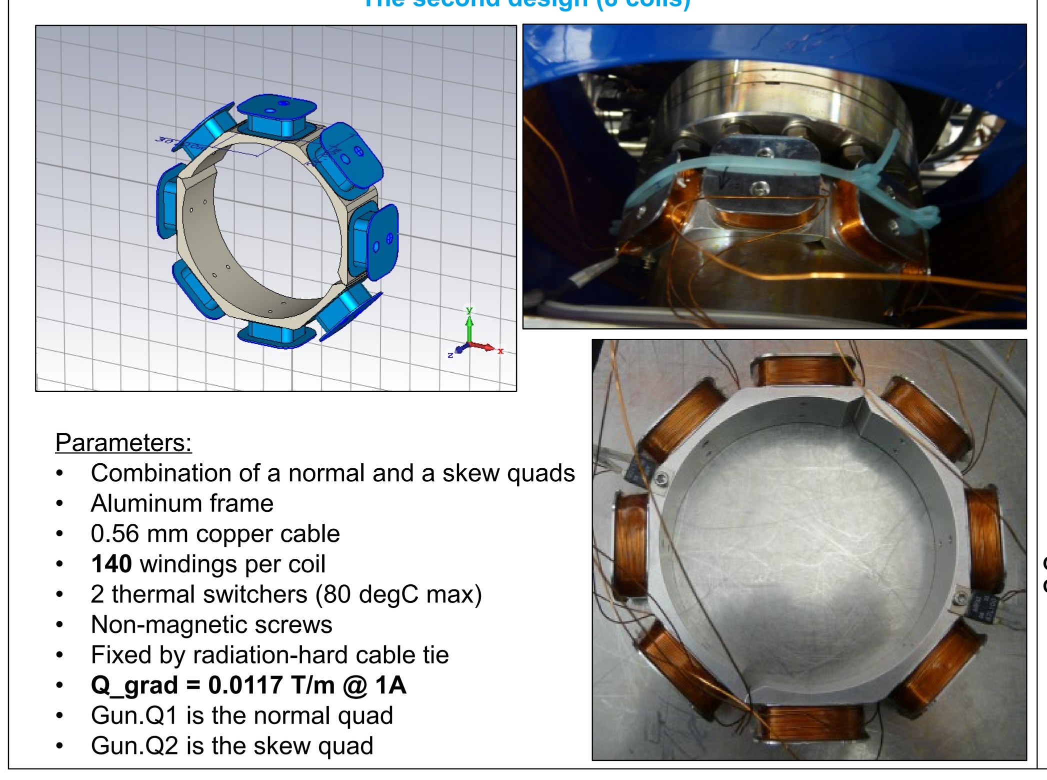
The knowledge of the fact that the beam asymmetry can be modeled by a rotational quadrupole allowed to make a design and produce compensating gun quadrupoles.

The first design (4 coils)



Parameters
- Aluminum frame
- 0.56 mm copper cable
- **180** windings per coil
- 2 thermal switchers (80 degC max)
- Non-magnetic screws
- Fixed by radiation-hard cable tie
- Usage with 3A power supply
- **Q_grad = 0.0207 T/m @ 1A**

The second design (8 coils)

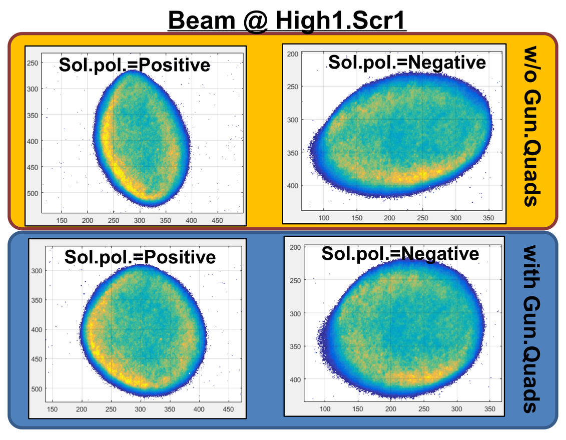


Parameters:
- Combination of a normal and a skew quads
- Aluminum frame
- 0.56 mm copper cable
- **140** windings per coil
- 2 thermal switchers (80 degC max)
- Non-magnetic screws
- Fixed by radiation-hard cable tie
- **Q_grad = 0.0117 T/m @ 1A**
- Gun.Q1 is the normal quad
- Gun.Q2 is the skew quad

Experiments with the gun quadrupole (with the 2nd design of the quadrupole)

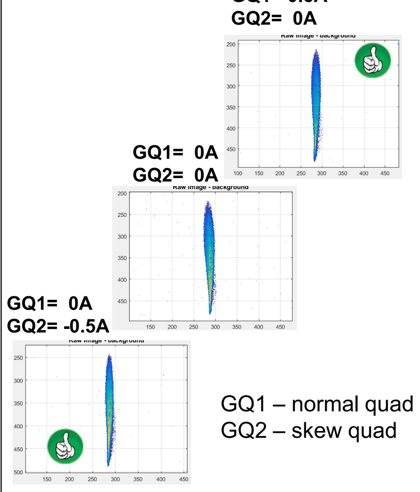
Transverse beam asymmetry compensation

The usage of the normal and skew quadrupoles combination allows to make round beam at the observation screens but not simultaneously.



Experiment on beam tilt (x-p_z) in LEDA

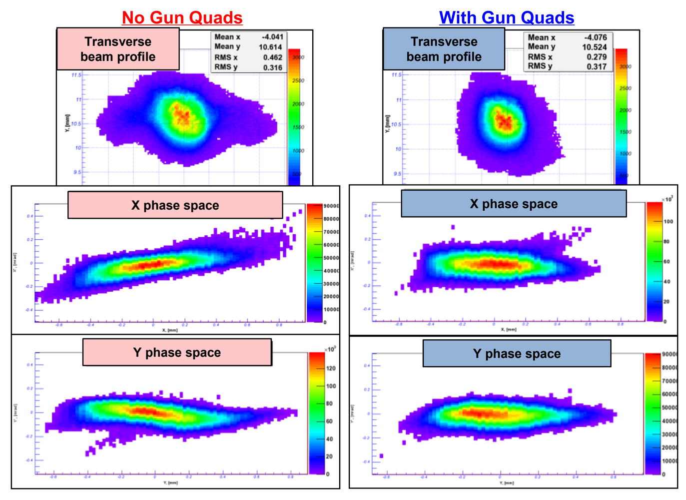
The observed tilt of the beam in the LEDA section is able to compensate by either GQ1 or/and GQ2



GQ1 – normal quad
GQ2 – skew quad

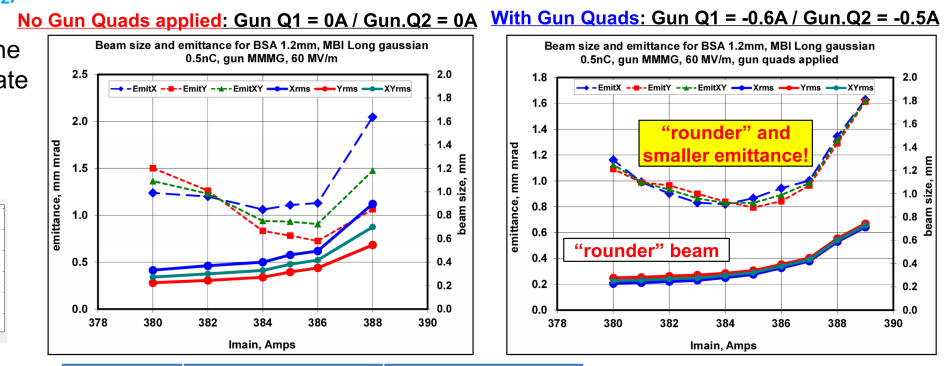
Emittance measurements

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



No Gun Quads applied: Gun Q1 = 0A / Gun.Q2 = 0A

With Gun Quads: Gun Q1 = -0.6A / Gun.Q2 = -0.5A



	No Gun Quads			With Gun Quads		
	x	y	xy	x	y	xy
Emittance, mm·mrad	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	

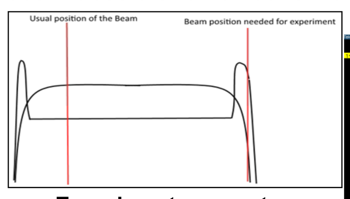
The beam emittance (horizontal and vertical phase spaces) becomes symmetric and smaller.

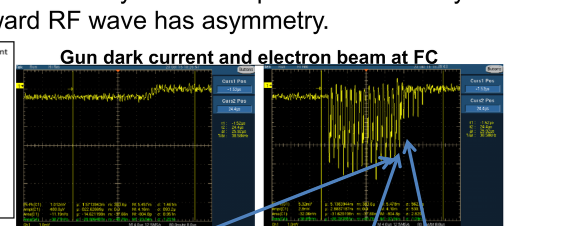
Other experiments

Some interesting experiments which were performed to find the source of the beam asymmetry. The presented experiments eliminated some ideas about sources of the beam asymmetry.

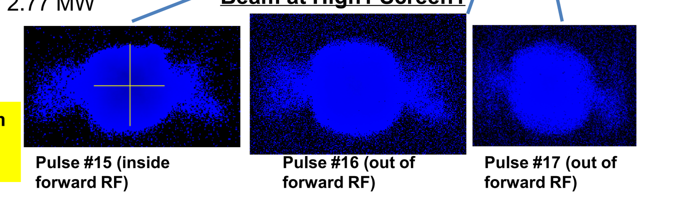
Experiment on e-beam acceleration w/o forward power

The idea of the experiment is to use only stored RF power in the cavity for the beam acceleration since forward RF wave has asymmetry.





Experiment parameters
- Gun power = 6 MW
- Booster power = 2.77 MW
- LT=90%
- BSA=1.2mm

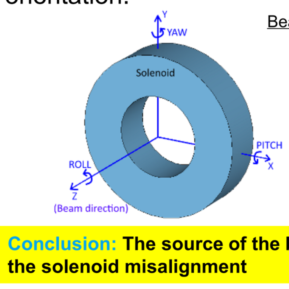


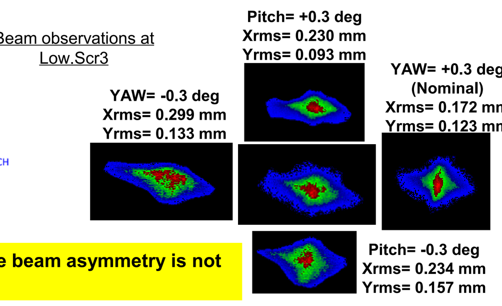
Pulse #15 (inside forward RF) | Pulse #16 (out of forward RF) | Pulse #17 (out of forward RF)

Conclusion: The beam asymmetry stays also w/o forward wave

Experiment on the main solenoid tilt

The idea is to check whether the beam shape depends on the main solenoid orientation.

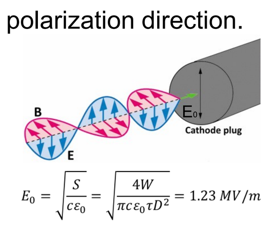




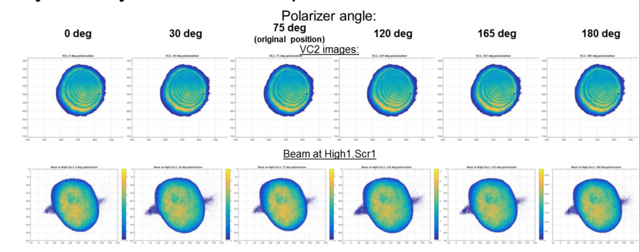
Conclusion: The source of the beam asymmetry is not the solenoid misalignment

Experiment on the influence of the photocathode laser polarization orientation on the beam asymmetry

Since the photocathode laser has transverse polarization, it could introduce transverse momentum to the beam at the moment of the emission. The idea is to check whether beam asymmetry orientation depends on the laser polarization direction.



$$E_0 = \sqrt{\frac{S}{c\varepsilon_0}} = \sqrt{\frac{4W}{\pi c\varepsilon_0\tau D^2}} = 1.23\ MV/m$$



Conclusion: The beam asymmetry does not depend on the laser polarization

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