Updated physical design of an L band normal conducting RF gun towards 2% duty cycle

RF pulse length 2 ms / 10 Hz for PITZ

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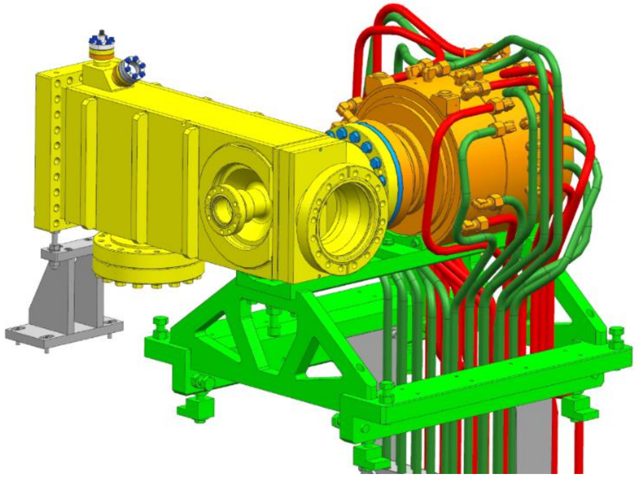
2021.12.16

Outline

- Motivation
- New gun design for PITZ
  - RF simulation
  - Dark current consideration
  - Beam dynamics optimization
  - Mechanical design and simulation
- Summary and outlook

Motivation

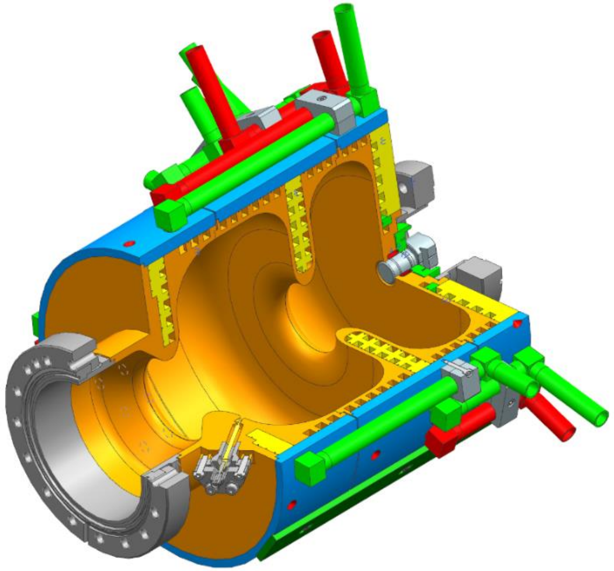


Gun 4

RF pulse 650 us / 10 Hz

(0.65% duty cycle)

Average power = 40 kW



Gun 5

RF pulse 1000 us / 10 Hz
(1% duty cycle)

Average power = 60 kW

New gun

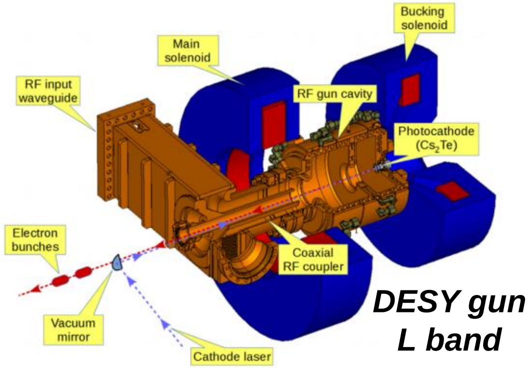
Similar beam performance

RF pulse 2000 us / 10 Hz

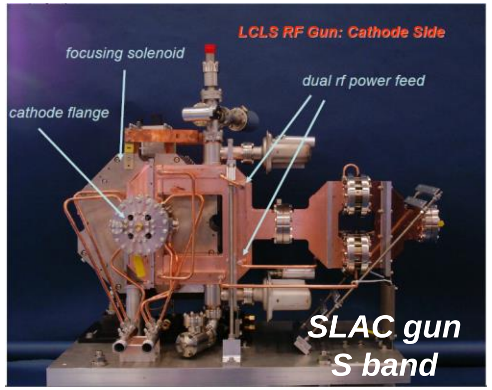
(2% duty cycle)

Two cavity shapes commonly used: pillbox & reentrant

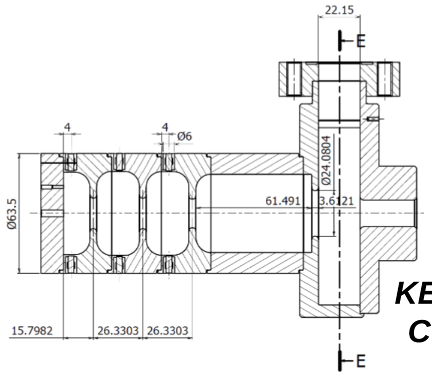
- **Pillbox cavity**
  - High RF frequency (L / S / C / X band), low duty factor
  - High RF breakdown threshold, high cathode gradient (> 60 MV/m), MeV beam, pancake beam w/o buncher system
  - Low duty factor (< 1%) due to thermal heating
  - Less radial field distortion (E_r & B_Φ)



DESY gun L band



SLAC gun S band

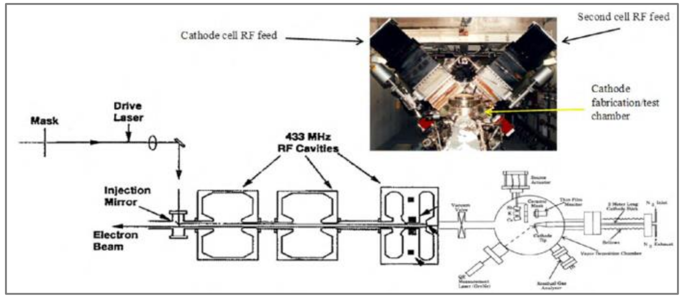


KEK gun C band

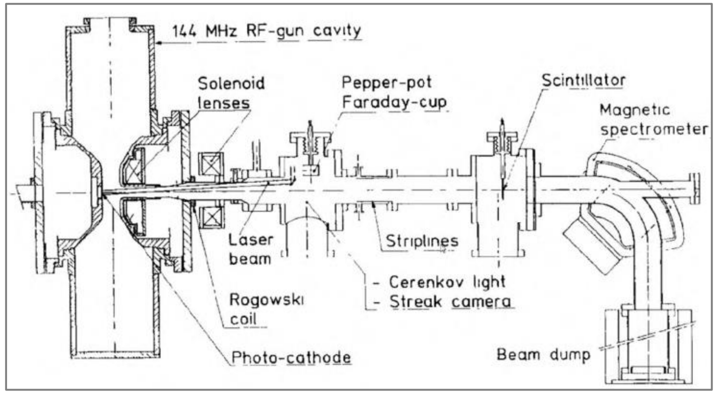
SLAC gun X band

- **Reentrant cavity**
  - Widely adopted at high duty cycle guns
    - Low frequency → large surface of cooling
    - High shunt impedance per unit length → high Ez/Pc
    - Low cathode gradient (~20 MV/m) and voltage, keV - MeV beam, cigar beam w/ buncher system
    - Higher radial field distortion

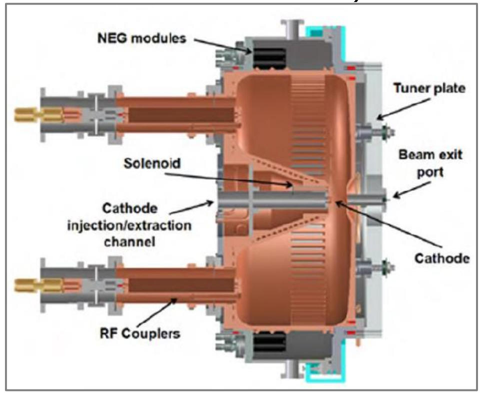
Boeing/LANL 433 MHz Gun, 8300 us/30 Hz



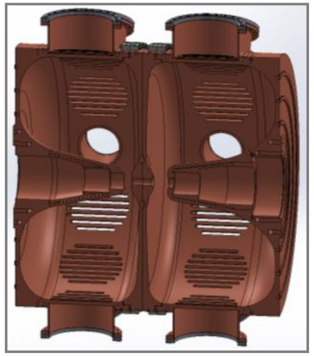
CEA 144 MHz Gun, 200 us/20 Hz



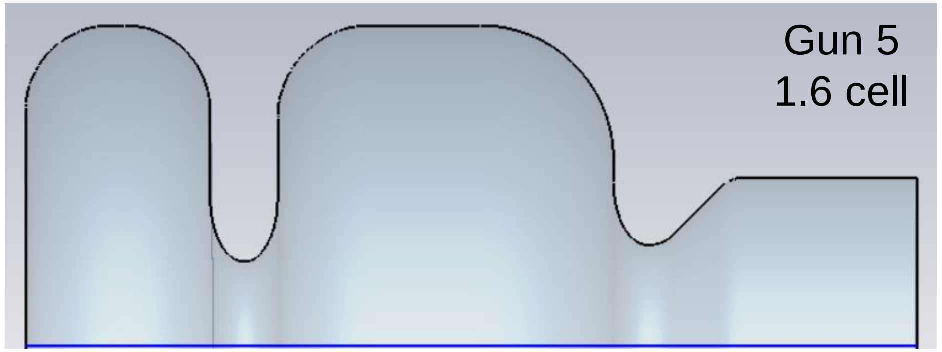
APEX 187 MHz Gun, CW

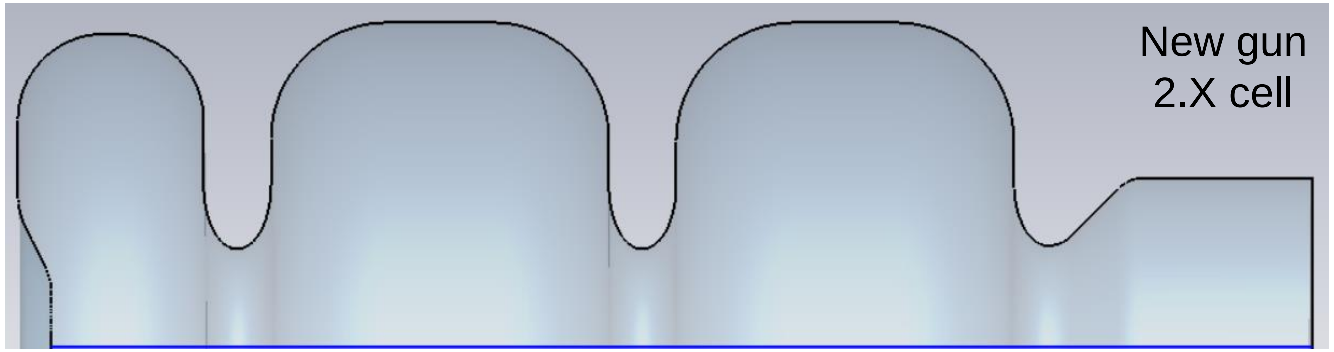


APEX-II 162.5 MHz Gun, CW



Basic idea: a combination of reentrant cavity + pillbox cavity





- Cathode cell has a nose cone

Beam quality

Emission gradient keeps constant, E_{cath}*sin(θ)

E_{cath} ↓

MMMG phase θ towards 90°

Half cell length is reduced

Duty cycle ↑, average loss density constant

Peak loss density = αH_{peak}^2 ↓

H_{peak} ↓

Reentrant cavity: E field is concentrated in gap, E_{cath} / H_{peak} ↑

Beam P_z keeps constant

One more cell to compensate P_z

State of the art

- R.A. Rimmer proposed an **L band** RF photocathode gun (EPAC 2002), duty factor 5%, individual RF power coupling

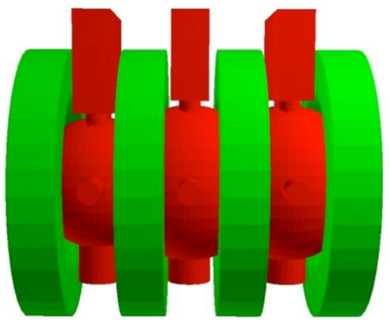


Figure 1. Solid model of proposed three-cell RF gun with solenoid compensation coils and power couplers.

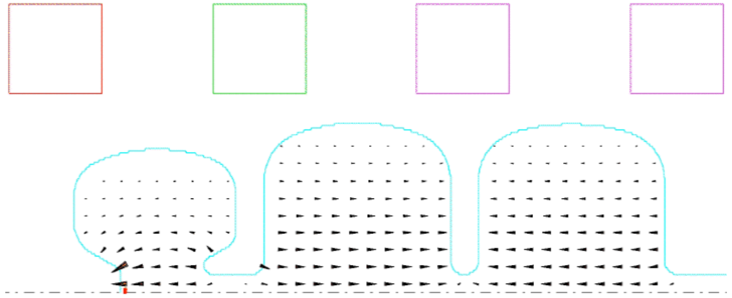
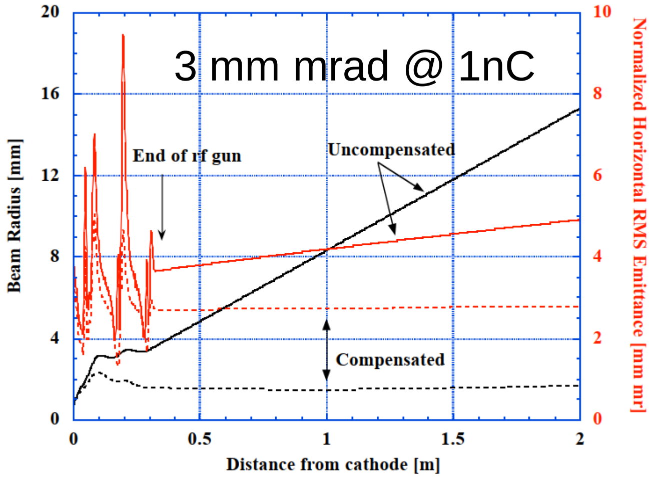


Figure 2. Profile of 3-cell RF gun showing MAFIA calculated electric fields and position of solenoid coils.

Table 1: Nominal operating parameters

	Gun cell	Cell 2 & 3
Frequency	1.3 GHz	1.3 GHz
Rep. rate	10 kHz	10 kHz
Duty factor	~5%	~5%
E_o	64 MV/m	43 MV/m
P_{peak}	581 kW	1550 kW
$P_{average}$	29 kW	77.5 kW
$P_{dens\ max}$	110 W/cm^2	107 W/cm^2



- S.P. Antipov proposed a compact **X band** 1 MeV electron linac for medical & industrial applications (NAPAC 2019)

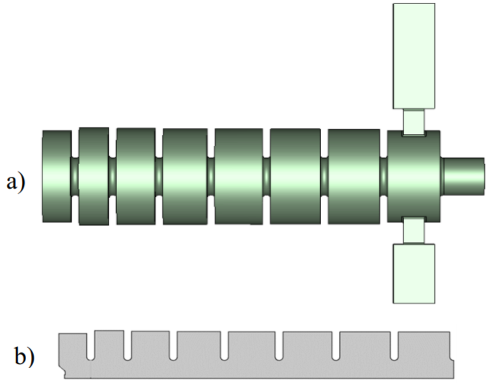


Figure 1: 8 cell SW accelerating cavity design with input waveguide coupler and waveguide dump: a) 3D model; b) accelerating cell's shape.

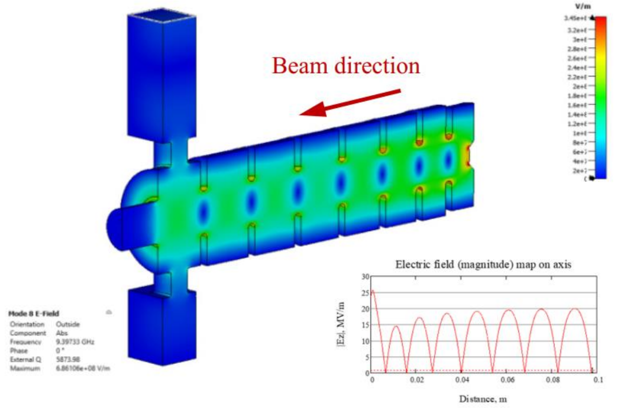


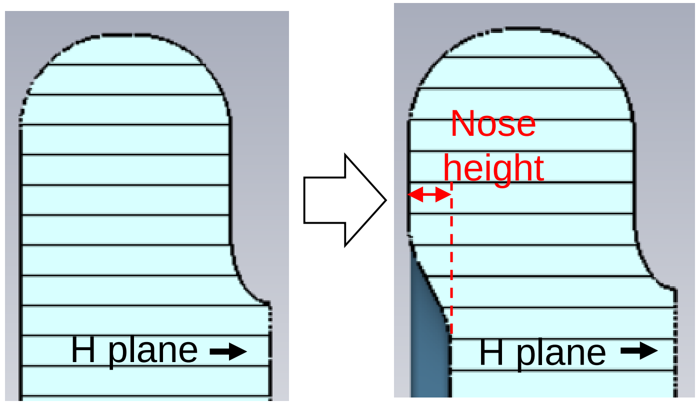
Figure 2: The π mode electric field map in the 8-cell 9.4 GHz accelerating cavity.

Table 1: Main 1 MeV Accelerator Parameters

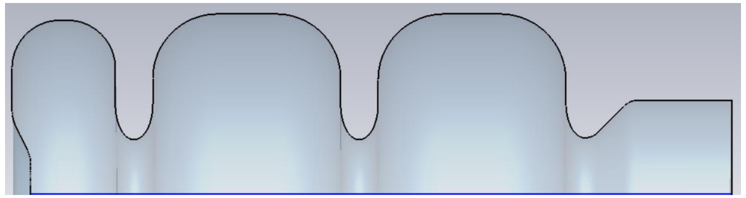
Operation frequency	9430 MHz
RF source	Magnetron
RF power	203 kW
Peak surface electric field	23 MV/m
Accelerating cavity length	111 mm
Shunt impedance	4.7 MOhm
Input beam energy	20 keV
Output beam energy	1 MeV

RF design of a new gun for PITZ

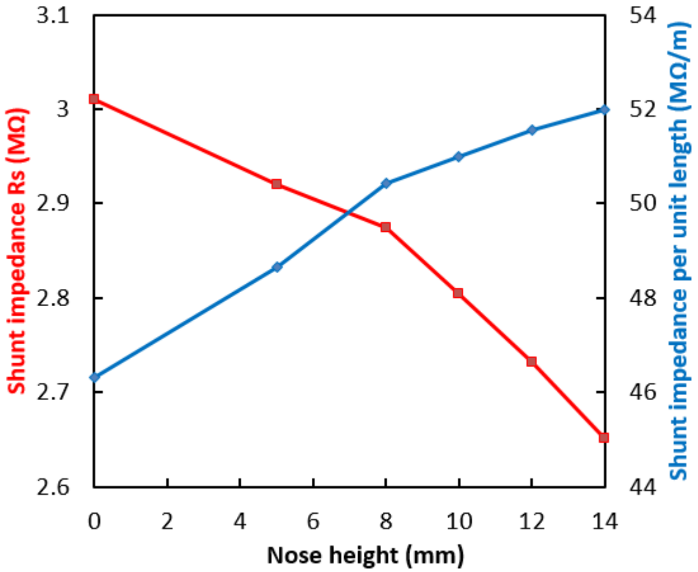
- Modified cathode cell (pillbox → reentrant)
  - Cathode cell radius → tune cavity frequency



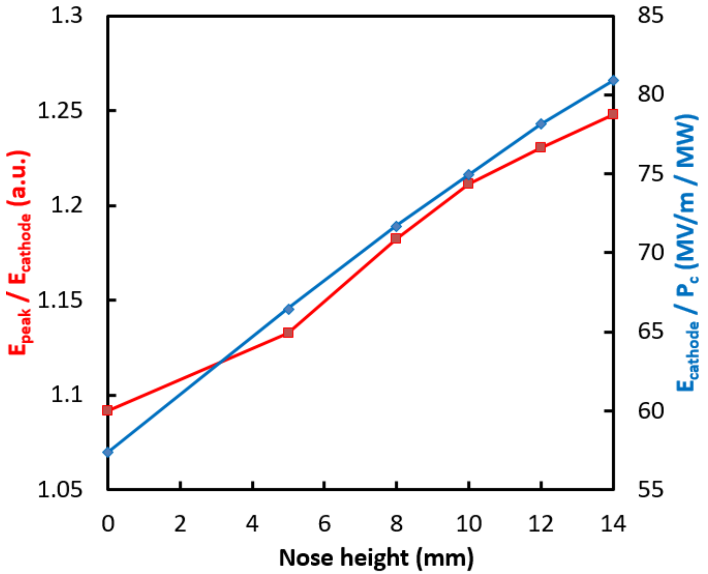
- 2.X cell RF gun

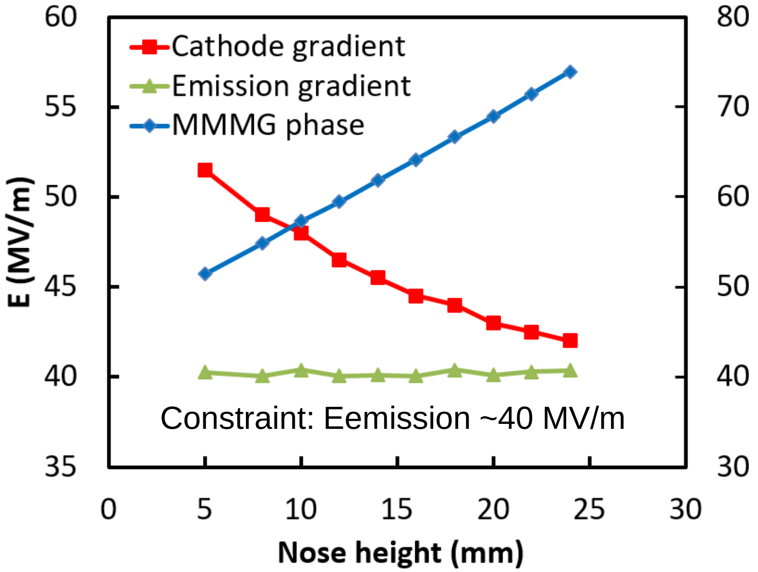


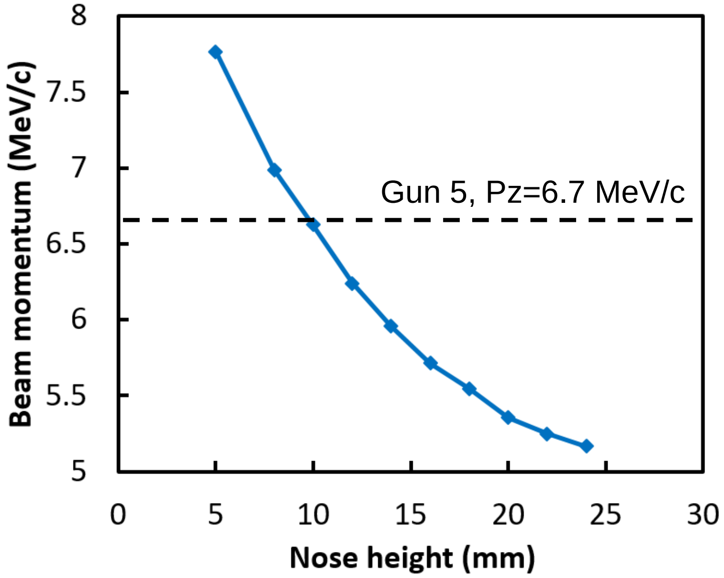
- Iris radius is enlarged (25 mm → 29 mm) to maintain similar mode separation (~5 MHz), stronger RF defocusing
- Emission gradient ~ 40 MV/m, similar to Gun 5
- Nose height = 10 mm, gun beam momentum similar to Gun 5 (6.7 MeV/c)



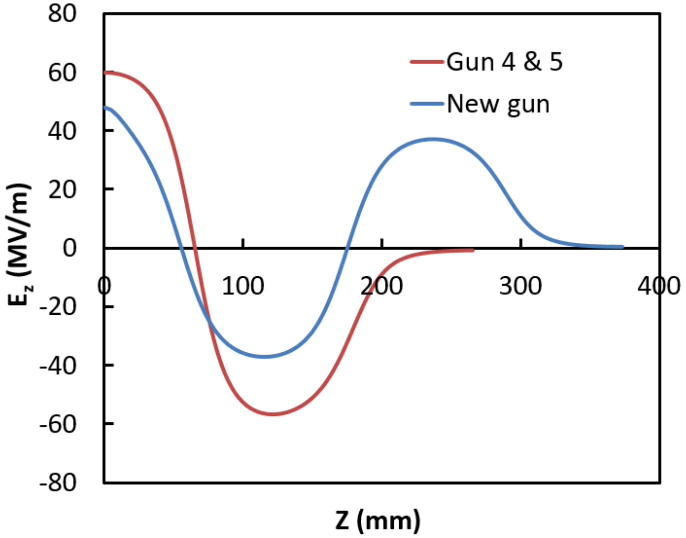
E field enhancement occurs at nose corner

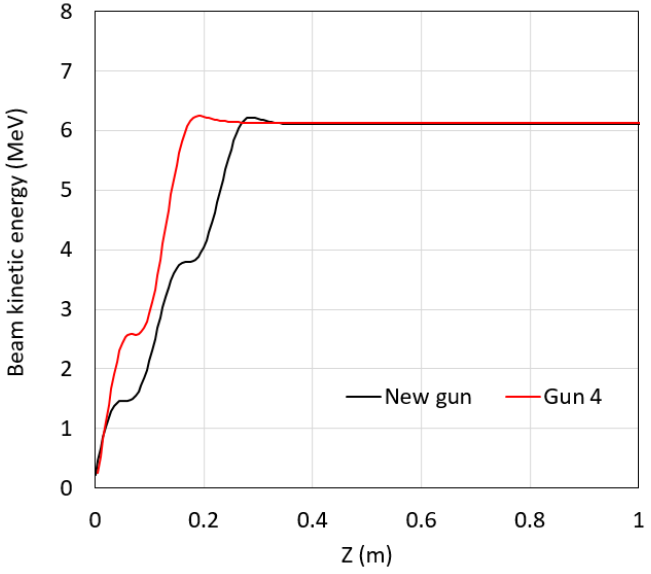






RF properties



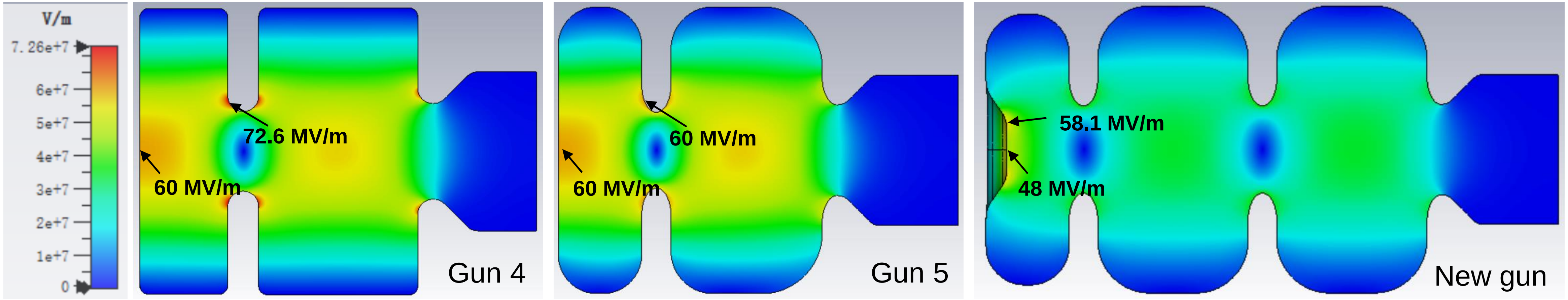


The beam in gun 4 is accelerated to 6 MeV more quickly than new gun → beam quality degradation? Need beam dynamics study.

	Gun 4	Gun 5	New gun
Mode separation (MHz)	5.1	6.1	5.4
Cathode E (MV/m)	60	60	48 (↓**20%**)
Field balance	**~1.05 : 1**	**~1.05 : 1**	**1.29 : 1**
Beam kinetic energy (MeV)	**6.1**	**6.1**	**6.1**
Peak surface E (MV/m)	72.6	60	58.1
Peak surface H (A/m)	97530	98792	65291
Peak RF power (MW)	**6.03**	**5.70**	**3.71 (↓35%)**
Unload Q0	23220	25448	27384
Peak surface loss density (W/cm2)	4475	4594	2005 (↓**56%**)
RF pulse duration (us)	**650**	**1000**	**2000**
Pulsed heating (degC)	35.1	44.6	39.0
RF pulse rep-rate (Hz)	10	10	10
Average surface loss density (W/cm2)	29.1	45.9	40.1
Average power loss (kW)	**39.2**	**57.0**	**74.3 (↑30%)**
Power loss in each cell (kW)	17.8 / 21.1	26.4 / 30.7	20.1 / 27.3 / 26.9

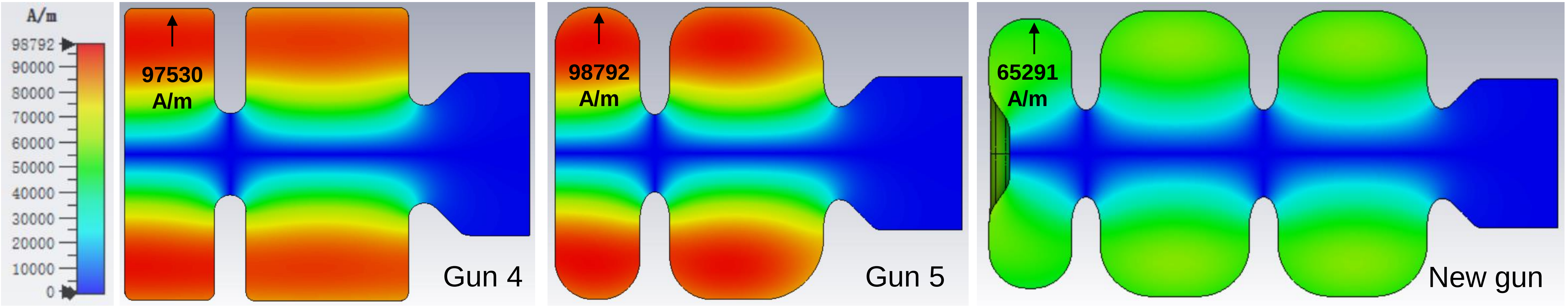
Gun 4, Gun 5 and new gun, E & H field maps

- E fields at working point



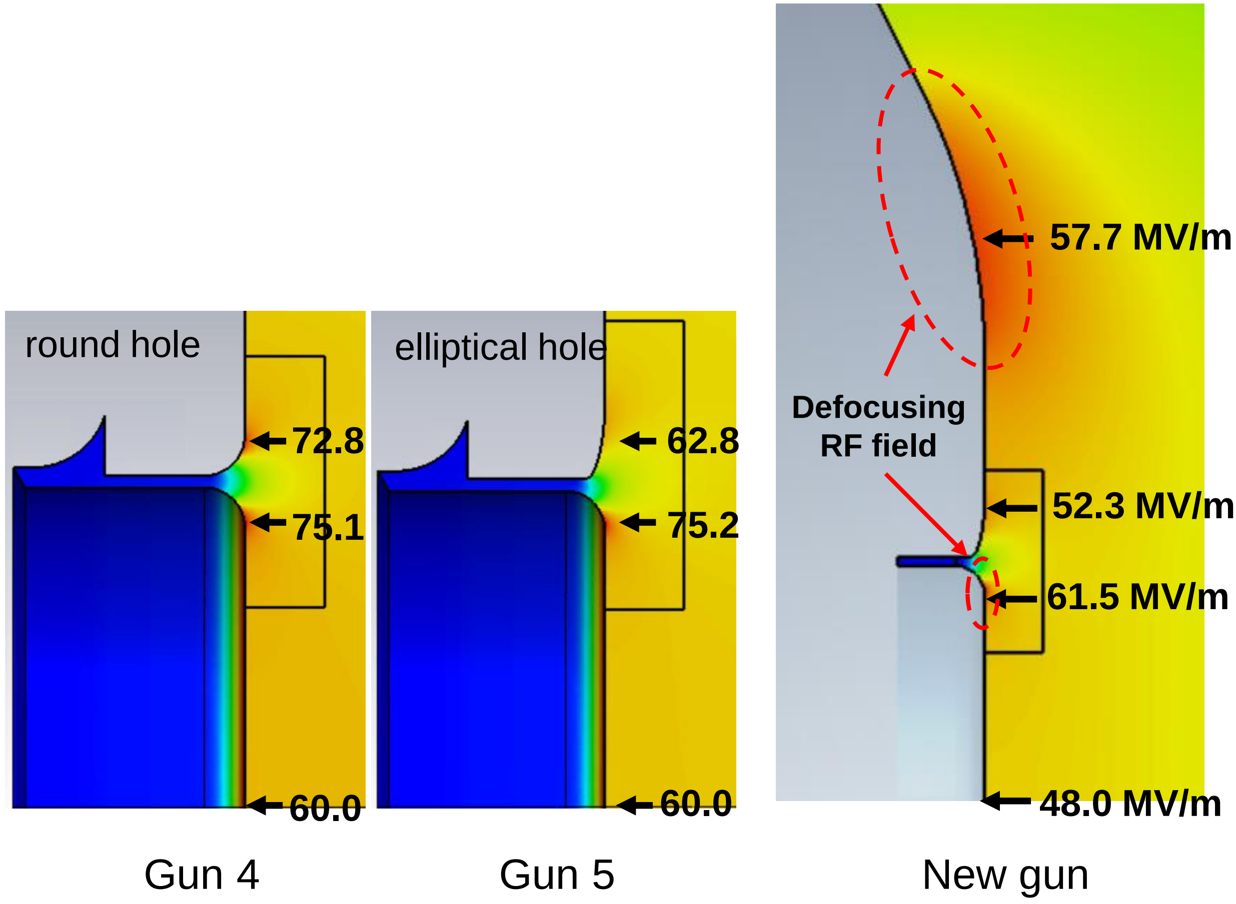
- H fields at working point, surface loss density ∝ H^2

Peak power loss density ↓ **56%**



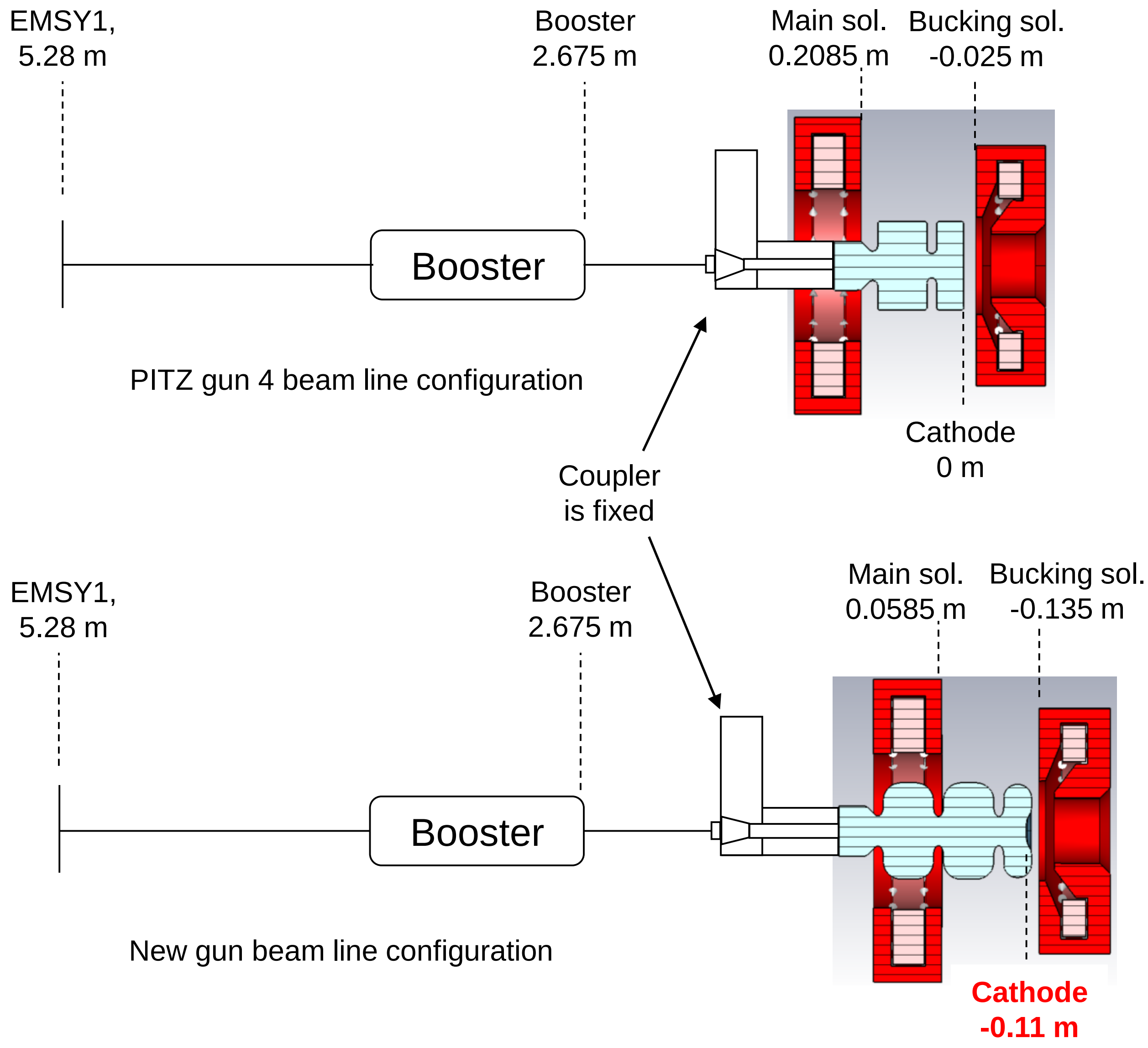
Considerations on dark current

- Plug vicinity: round plug corner + elliptical hole, similar dimensions with Gun 5
  - Surface E field strength is lower than Gun 5, lower field emission strength
  - E field enhancement appears at plug corner and nose cone. Defocusing RF field, low dark current transmit ratio
  - Gun 4 (650 us / 10 Hz / 60 MV/m)
    - Dark current in one RF macro pulse~100 uA
    - Average dark current ~650 nA
  - Gun 5 (1000 us / 10 Hz / 60 MV/m)
    - In RF conditioning stage, seems much lower dark current from image, dark current measurement ongoing
  - New gun (2000 us / 10 Hz / 48 MV/m)
    - If dark current of Gun 5 in measruemnt < 30 uA, average dark current is < 300 nA
    - With a much lower E field, the expected average dark current of new gun << 600 nA, smaller than Gun 4



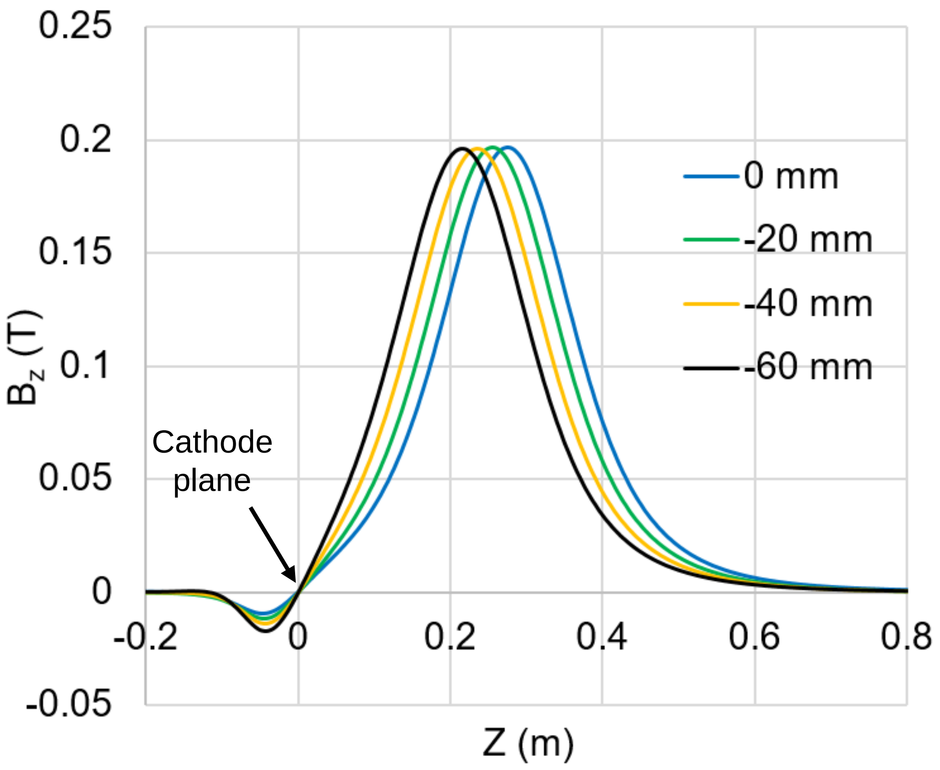
Beam dynamics optimization based on PITZ beam line

- Minor change to existing beam line
  - RF gun is the only device needs to be replaced
  - Gun waveguide, booster and bean line diagnostics keep unchanged
  - Gun, solenoids and loadlock system move towards upstream by 0.12 m (1 cell length)
  - Distance between main solenoid and cathode plane is reduced by 0.04 m (better emittance compensation)
- Beam dynamics optimizations
  - Laser transverse homogenous; longitudinal flat top 2 / 21.5 \ 2 ps
  - Cs_2Te cathode, thermal emittance 0.847 um/mm (0.55 eV)
  - ASTRA + Multi-Objective Genetic Algorithm (MOGA)
    - E_{cath} = 48 MV/m
    - Variables: (1) laser transvers size, (2) gun phase, (3) solenoid Bz, (4) solenoid position, (5) booster Ez
    - Objective: minimal projected emittance at EMSY1

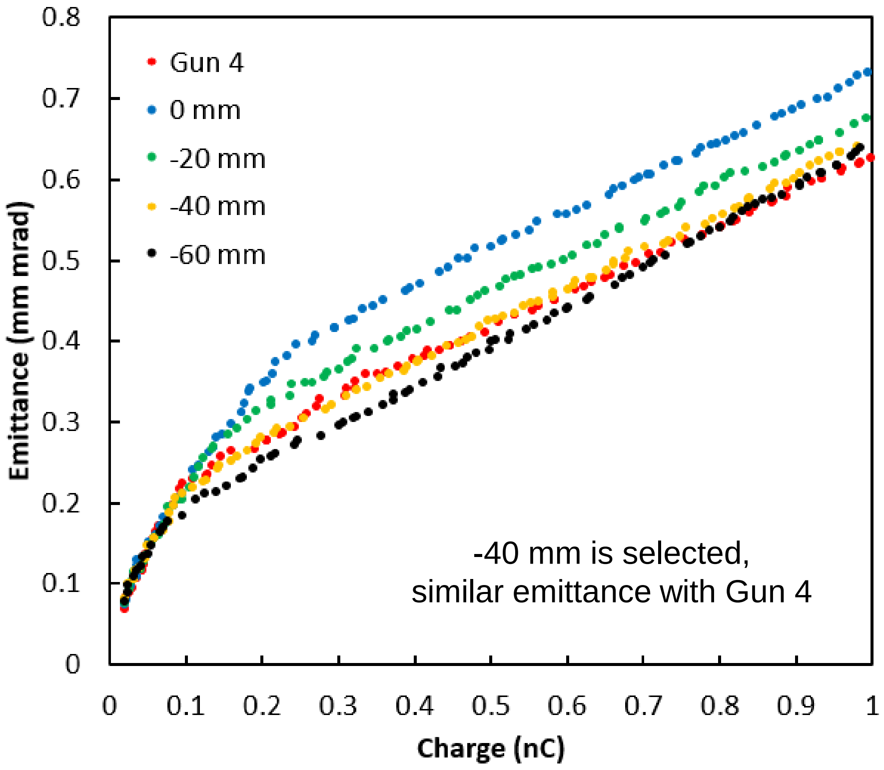


Main solenoid position

Main solenoid closer to the cathode yields better transverse projected emittance



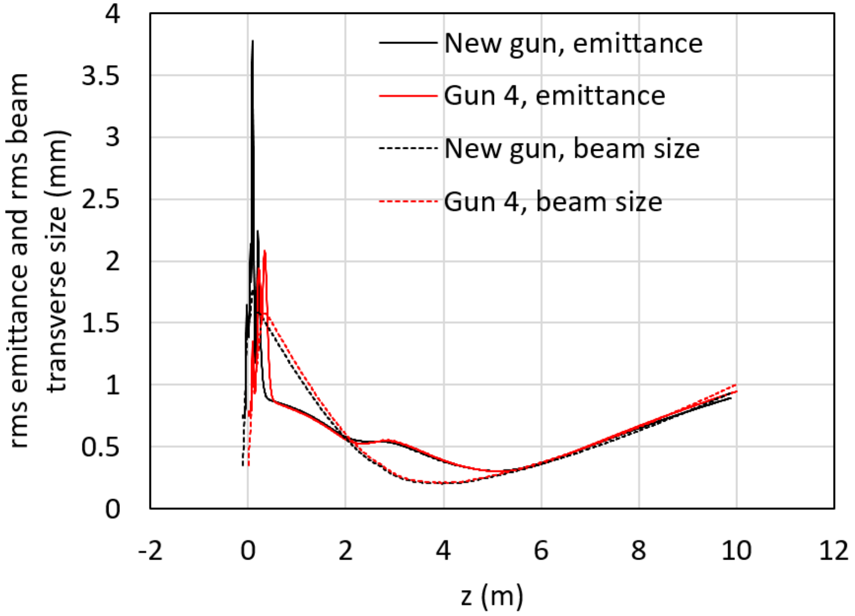
0 mm : Gun 4 solenoid configuration;
-20 mm : main solenoid to cathode distance is reduced by 20 mm

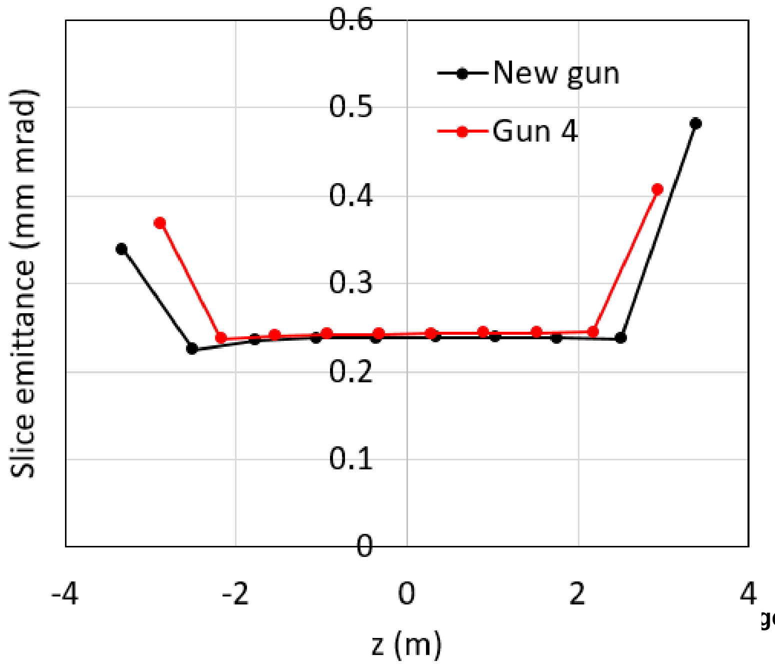


Sebastian's comments : At Gun 4 the solenoid can be moved by about **75 mm towards the cathode**. This is needed in order to mount the DN100CF-flange. For Gun 5 the Solenoid can be moved even further to allow the exchange of the pick-up.

Optimal parameters for 250 pC charge

		Gun 4	New gun
Cathode laser	Temporal profile	Flat top 2 / 21.5 \ 2 ps	Flat top 2 / 21.5 \ 2 ps
	Transverse distribution	homogenous	homogenous
	XYrms (mm)	0.264	0.245
	Thermal emit. (mm mrad)	0.224 (74%)	0.208 (68%)
RF gun	**Ecath (MV/m)**	**60**	**48**
	MMMG phase (deg.)	45.15	57.28
	Phase (deg.)	1.13	4.67
	Eemission (MV/m)	**43.4**	**42.4**
	Max Bz (T)	-0.2246 (~370A)	-0.17687 (~290 A)
Booster	Max E (MV/m)	12.0	12.0
	Phase (deg.)	0	0
e- beam @EMSY1	Charge (nC)	0.25	0.25
	Energy @ gun exit (MeV)	**6.13**	**6.10**
	Energy @ EMSY1 (MeV)	16.5	16.5
	Energy spread (keV)	35.6	57.5
	Rms bunch length (mm)	**1.827**	**2.104 (↑15%)**
	XYrms (mm)	0.295	0.275
	Proj. emit. (mm mrad)	**0.303**	**0.306**





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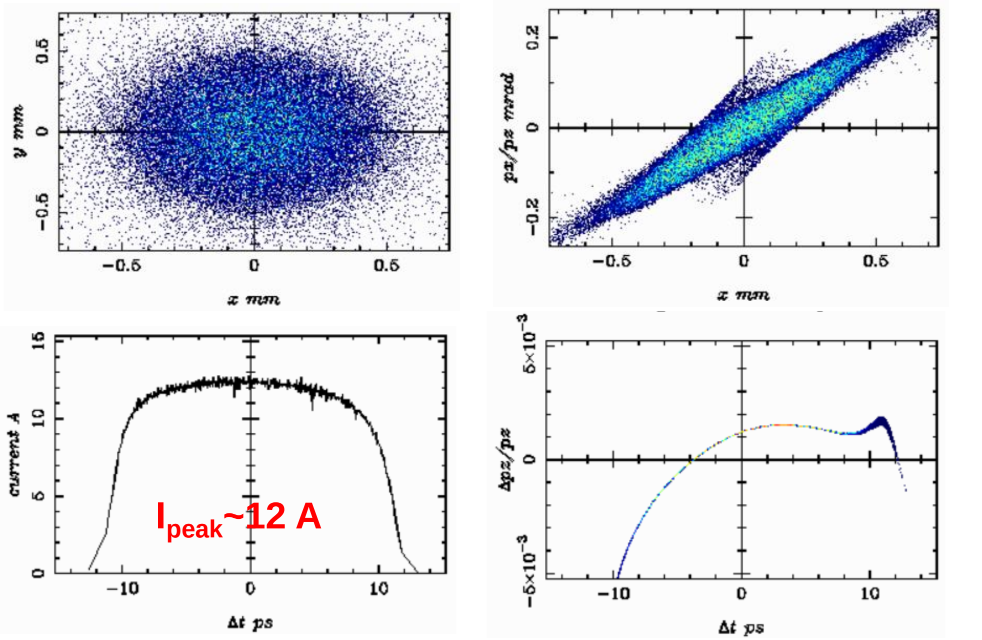
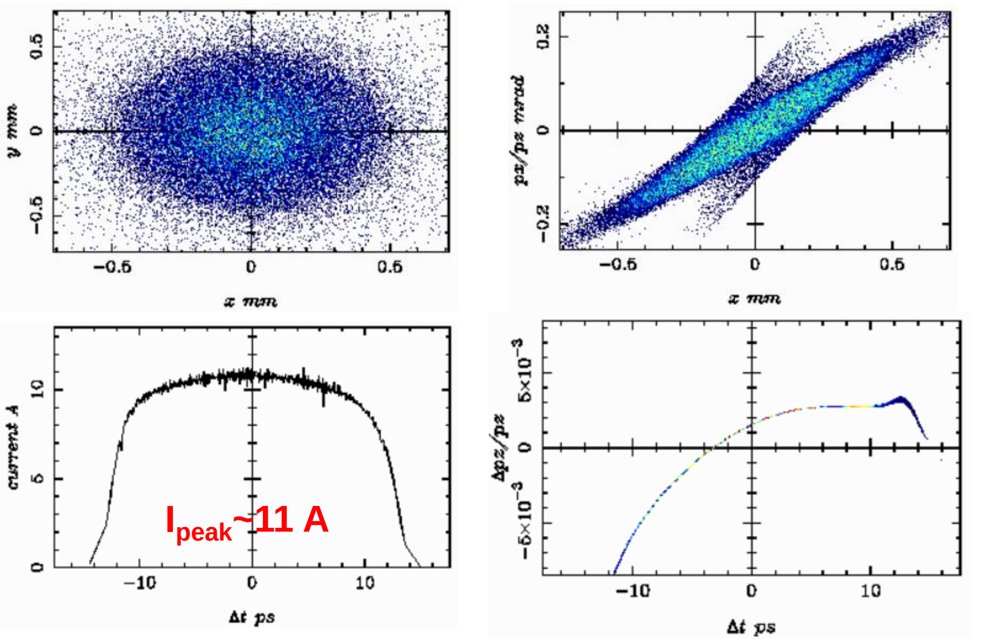
Gun 4, phase space at EMSY1

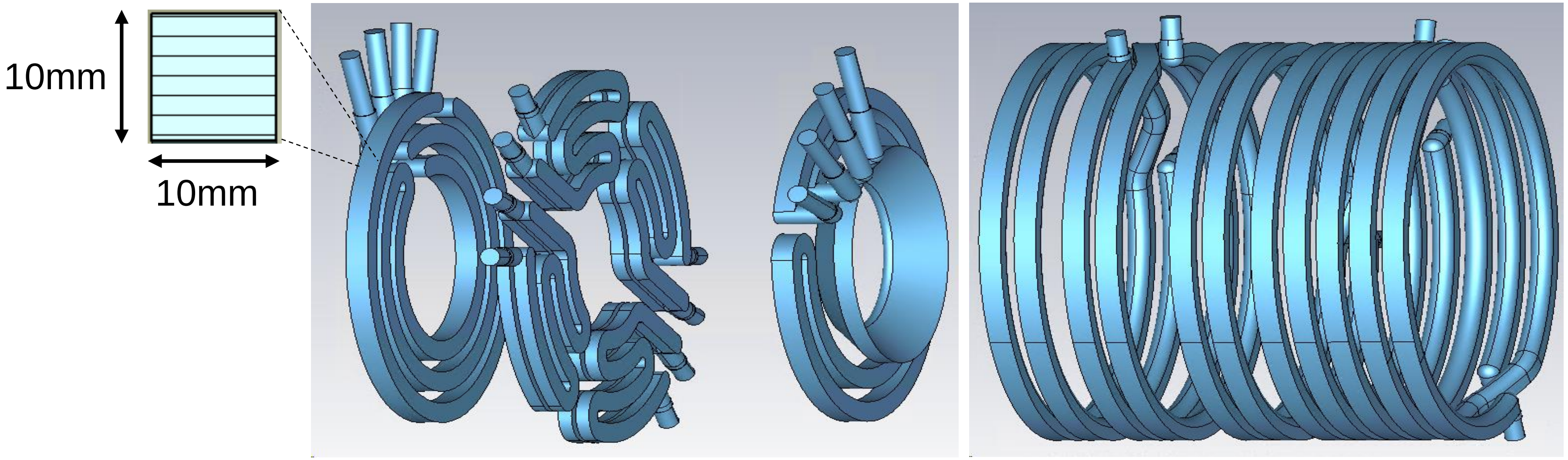


New gun, phase space at EMSY1



Mechanical design and simulation

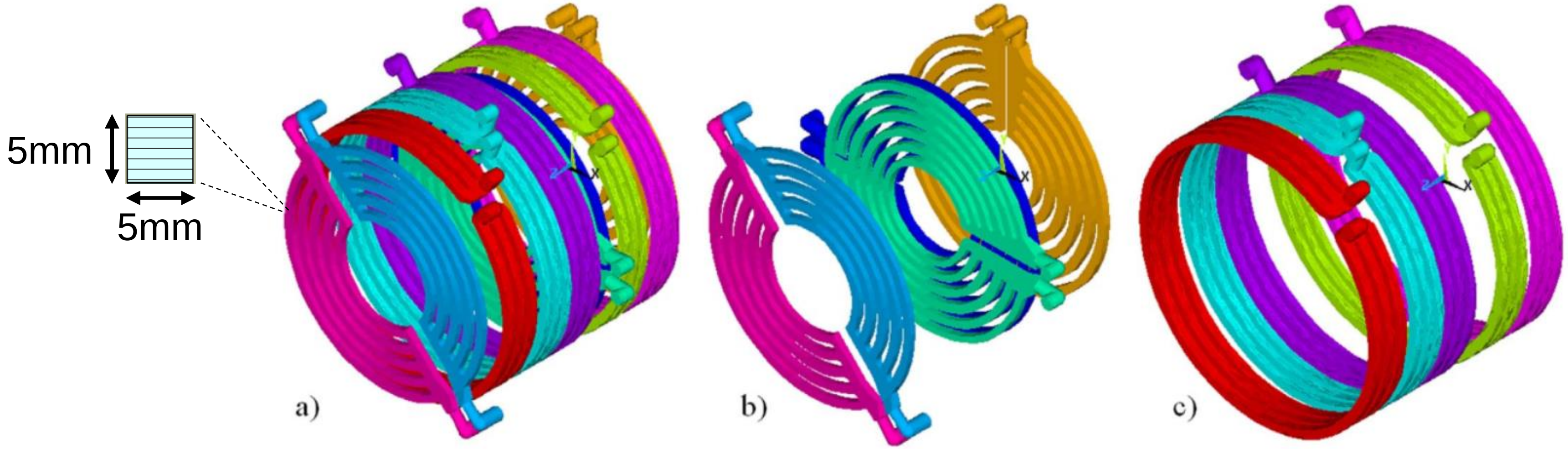
Water cooling scheme, two choices : PITZ Gun 4 & Gun 5



Gun 4 cooling pipe

(Courtesy of Sebastian)

- 12m^3/h water flow, ~2 m/s
- Already demonstrated to handle 40 kW RF heating



Total iris radial cooling

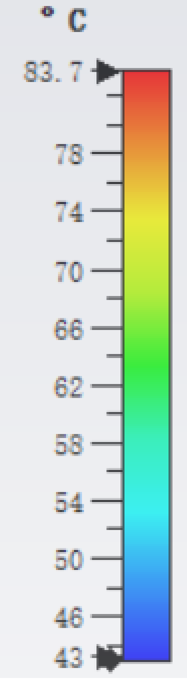
Gun 5 cooling pipe, enhanced cooling performance (see NIM A 854 (2017) 113-126)

- Cut plane area ↓, heat transfer coefficient ↑ (same water speed)
- Total heat exchange area ↑
- Target is 60 kW RF heating load, in RF conditioning phase
- Water channels almost cover all the inner surface, very good optimization

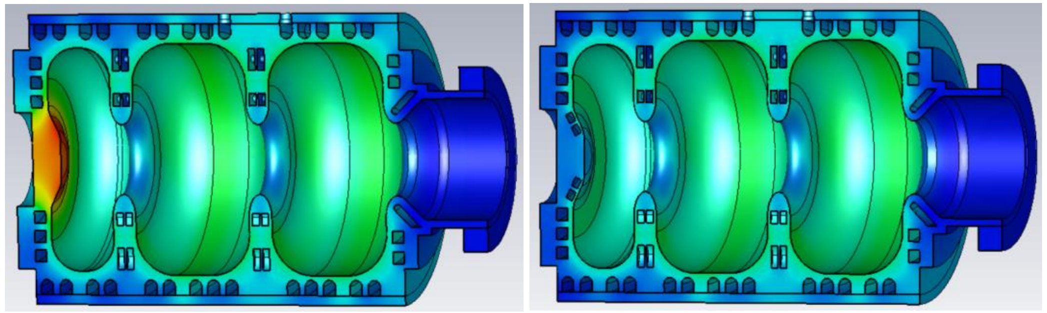
Temperature and stress distribution of new gun

Water conditions: 40 degC, 2 m/s; power loss 74.3 kW

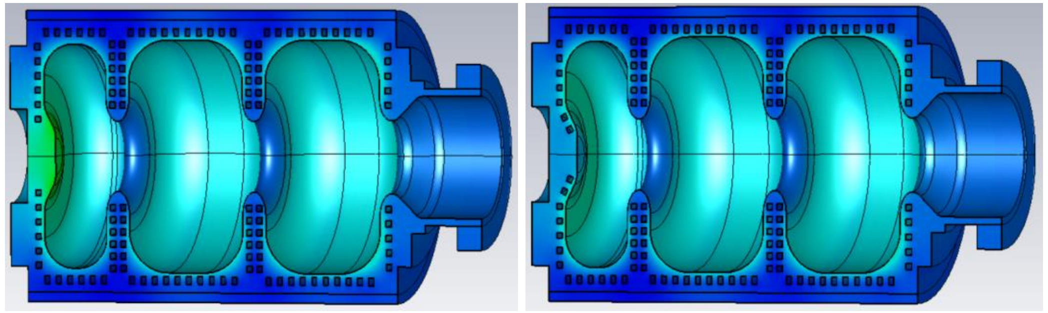
Temperature plot



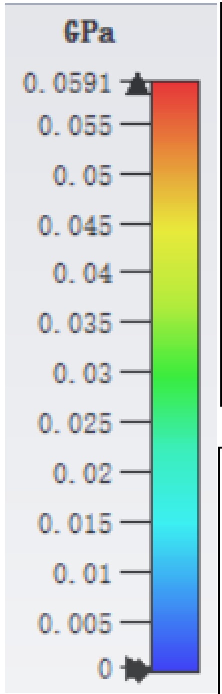
Gun 4 type cooling, w/o vs w/ nose cooling



Gun 5 type cooling (use simplified symmetrical channels),
w/o vs w/ nose cooling



Stress plot



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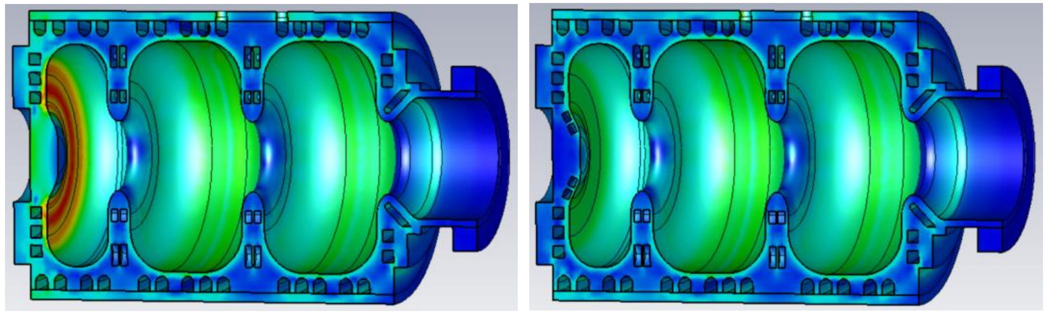
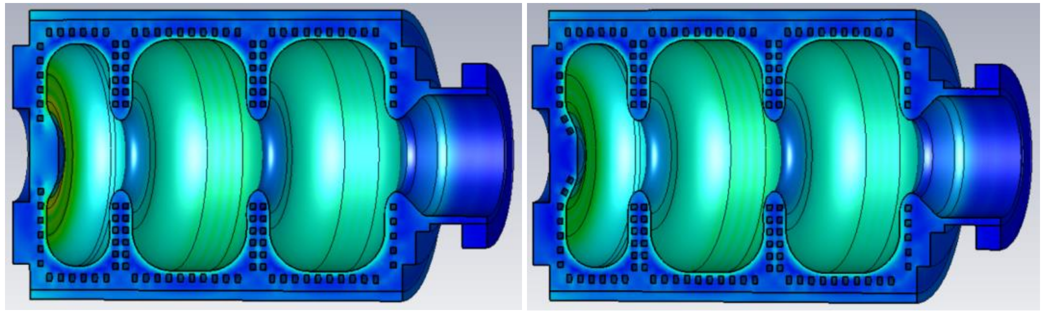


Gun 5 type cooling, w/o vs w/ nose cooling



- Empirical heat transfer coefficient was used for a quick comparison, ~20% temperature and stress underestimation.
- Water temperature rise inside the channel was not considered, estimated total T rise at exit ~ 5.5 degC

Temperature and stress distribution of new gun

Water conditions: 40 degC, 2 m/s

	RF heating (kW)	Cathode center T rise (degC)	Peak T rise (degC)	Peak stress (MPa) [3]	Peak deformation (um)	Detuning sensitivity (kHz/kW)
Gun 4 [1]	40	18.0	22.1	36.1	44.8	- 5.7
Gun 5 [2]	63.1	~10	17.7	35.4	~28	- 2.3
New gun + Gun 4 cooling	74.3	39.0	43.7	59.1	73.6	- 4.2
New gun + Gun 4 cooling, w/ nose cooling	74.3	9.7	22.6	36.8	69.3	- 3.6
New gun + Gun 5 cooling	74.3	21.5	24.6	42.4	62.9	- 2.5
New gun + Gun 5 cooling, w/ nose cooling	74.3	11.6	18.8	29.4	64.4	- 2.3

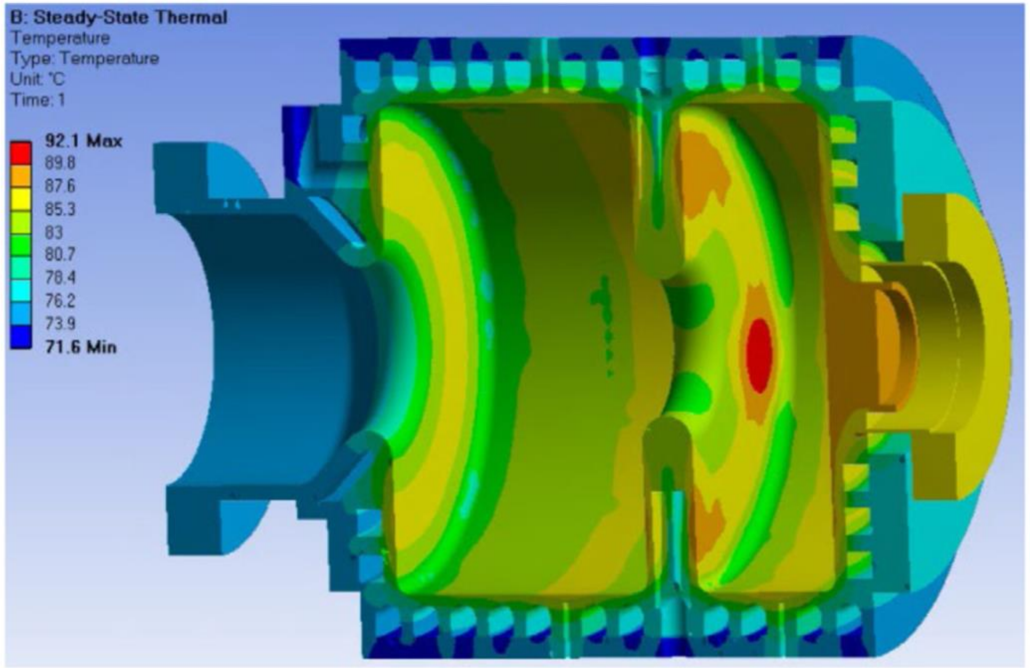
[1] NIM A, 1004 (2021) 165344
[2] NIM A, 854 (2017) 113–126
[3] Yield strength limit of Cu is ~62 MPa

Conclusion

- New gun aiming for **2 ms / 10 Hz** operation mode has been proposed for PITZ.
  - The required peak RF power 3.71 MW (~62% of Gun 4), operation stability can be improved, i.e. less discharge in waveguide, MP free region of RF window.
  - Lower surface E field → lower dark current in one RF macro pulse. But higher duty cycle, average dark current? Dark current measurements of Gun 5 can give more clues.
  - A similar beam emittance with Gun 4 but longer bunch has been achieved.
  - Gun 5 type cooling applied, all specs looks good vs. gun 4 with a duty factor increase of ~3
  - Nose cooling channel is helpful to reduce temperature of cathode vicinity.
- The structure (reentrant cathode cell + pillbox accelerating cells) can be extend to other frequency RF guns to increase duty cycle, e.g. kHz UED / UEM using S band RF guns.

Backup slice

Gun 4 and 5 thermal performance



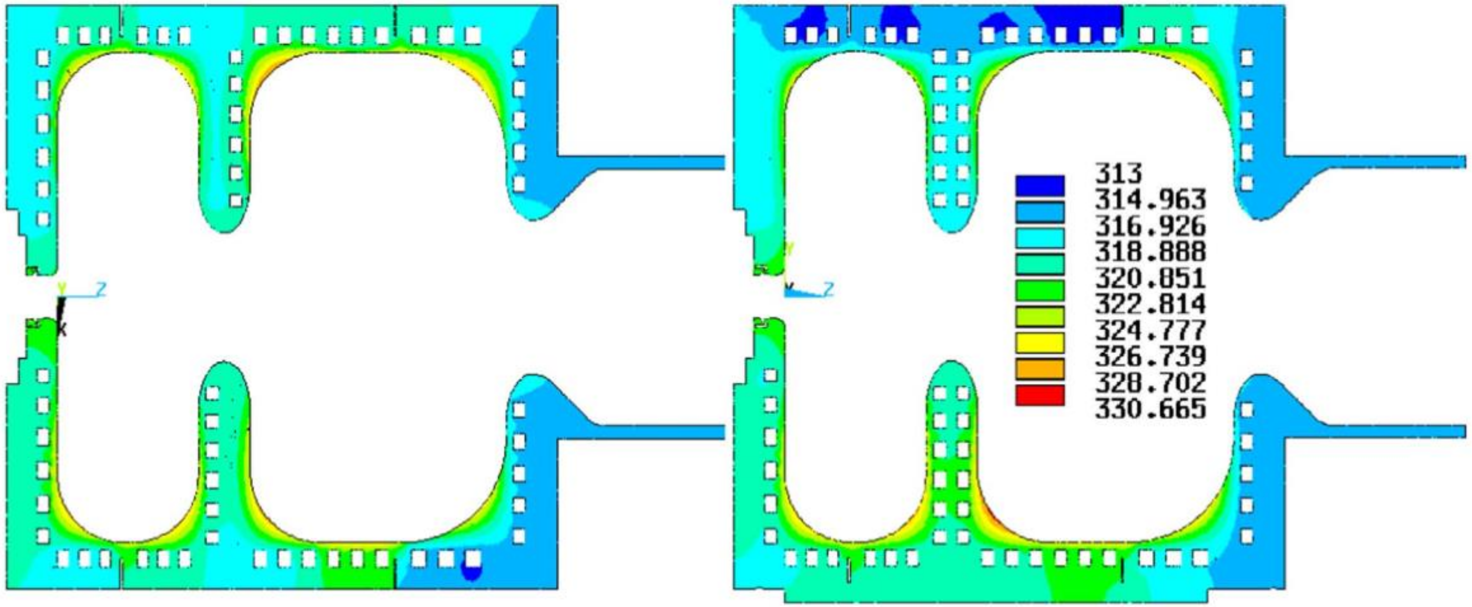
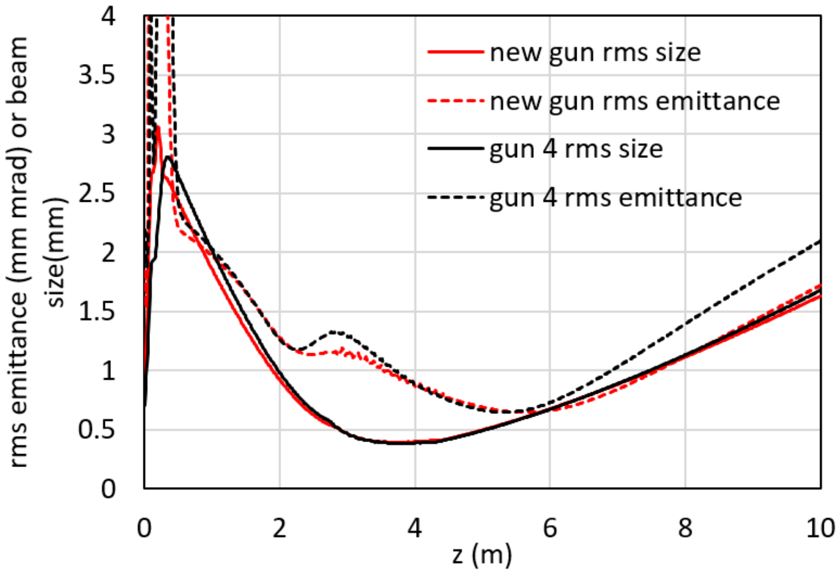


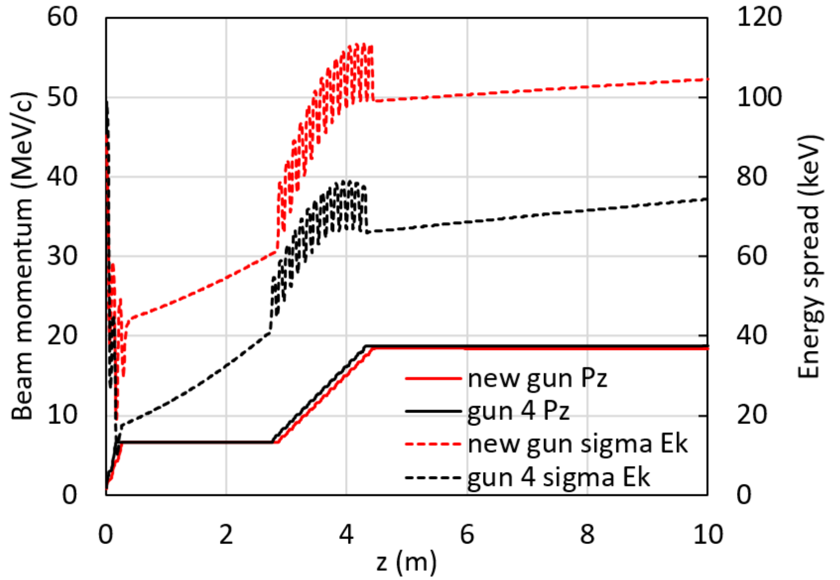
Fig. 19. The temperature distribution in the metal cavity parts for two perpendicular cross sections.

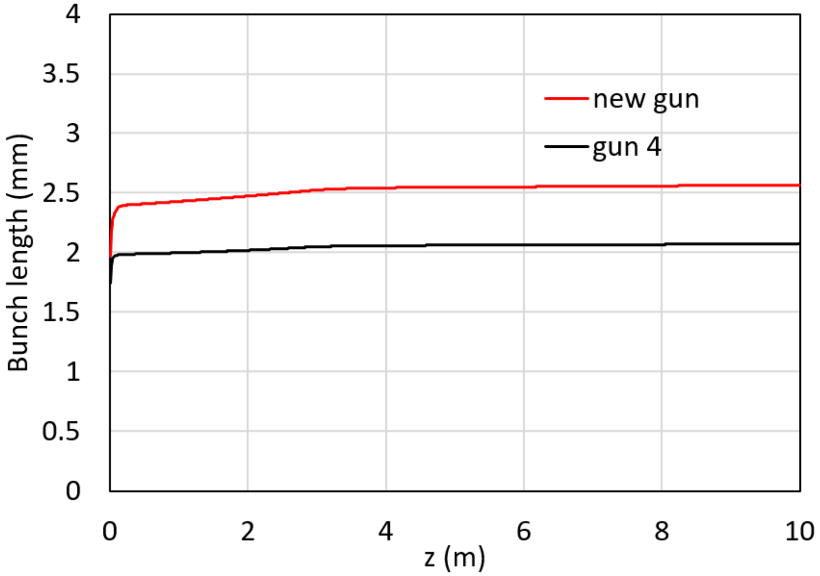
Gun 4, 70 degC water, 2 m/s
40 kW power loss
Max. T rise 22.1 degC
Cathode center T rise ~ 18 degC

1 nC case

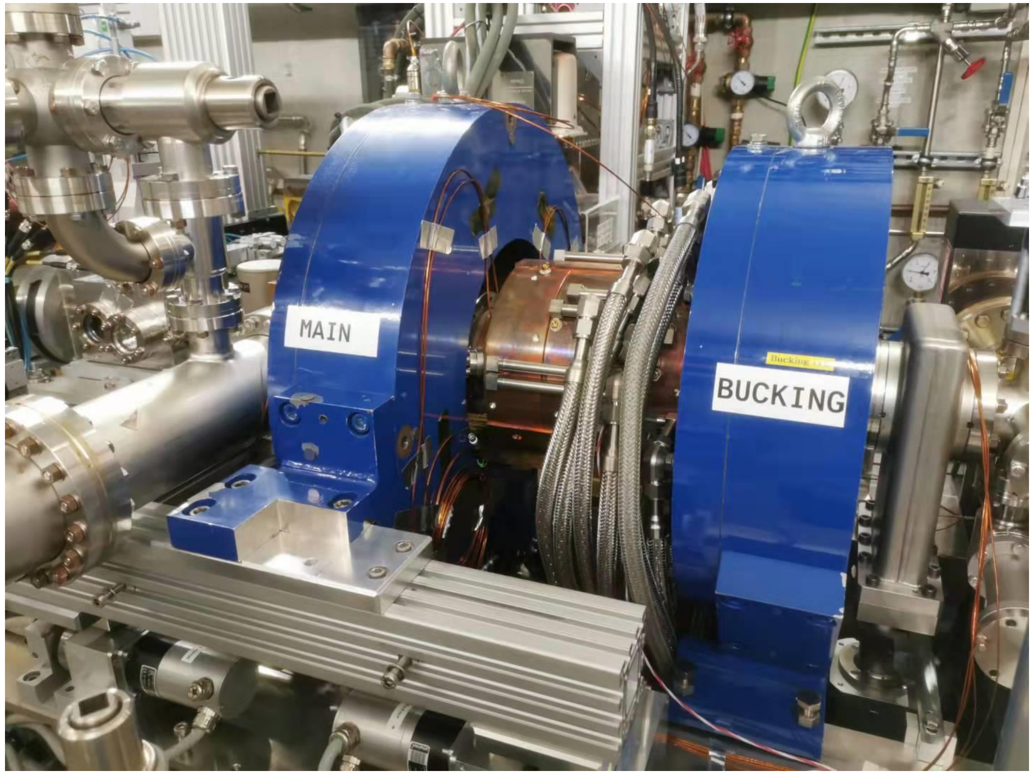
Optimum parameters		
	Gun 6	Gun 4/5
Ez (MV/m)	48	60
Gun phase (deg)	2.35	-1.34
Booster z (m)	2.785	2.675
Booster E (MV/m)	13.68	14.04
Booster phase (degree)	0	0
Solenoid Bz(T)	0.1727	0.2261
EMSY1_z(m)	5.28	5.28
emit(um)@EMSY1	0.661	0.648
xrme(um)@EMSY1	0.544	0.539
Ekin(MeV)@EMSY1	17.9	18.3
zrms(mm)@EMSY1	2.55	2.06
Delta_E(keV)@EMSY1	99.9	67.5







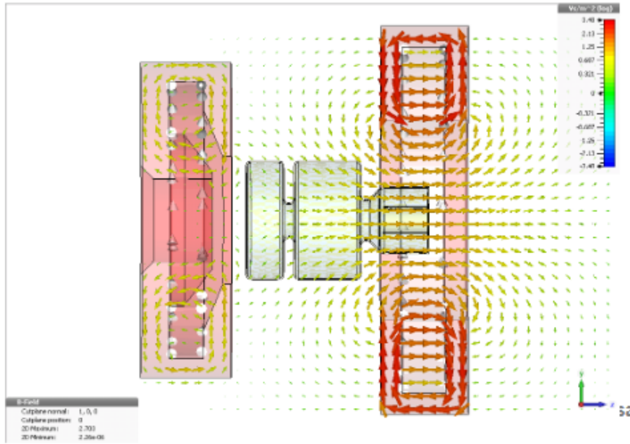
Gun 5 + solenoids

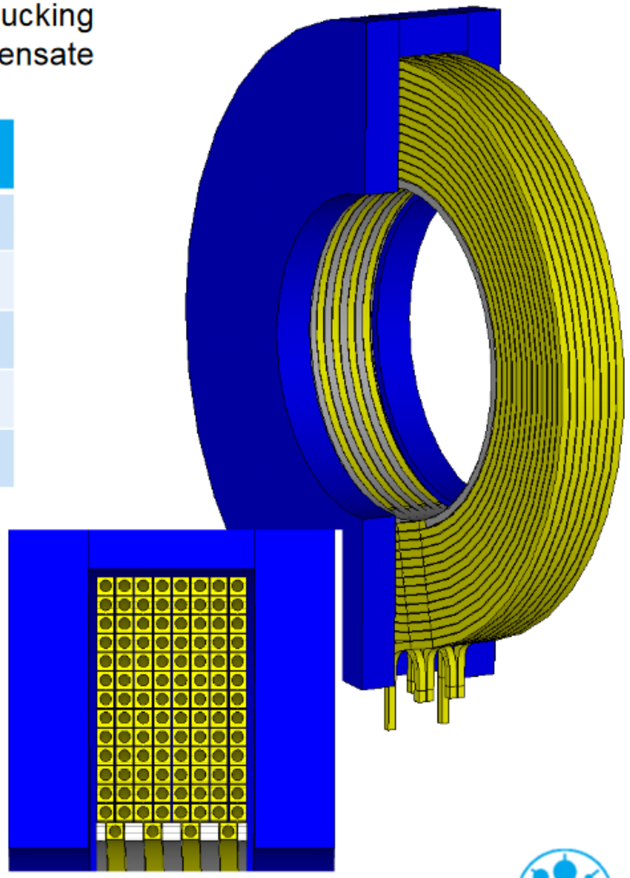


Solenoids

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





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