Preliminary design of a new L band rf gun for a higher duty cycle operation and higher operation reliability

Guan Shu

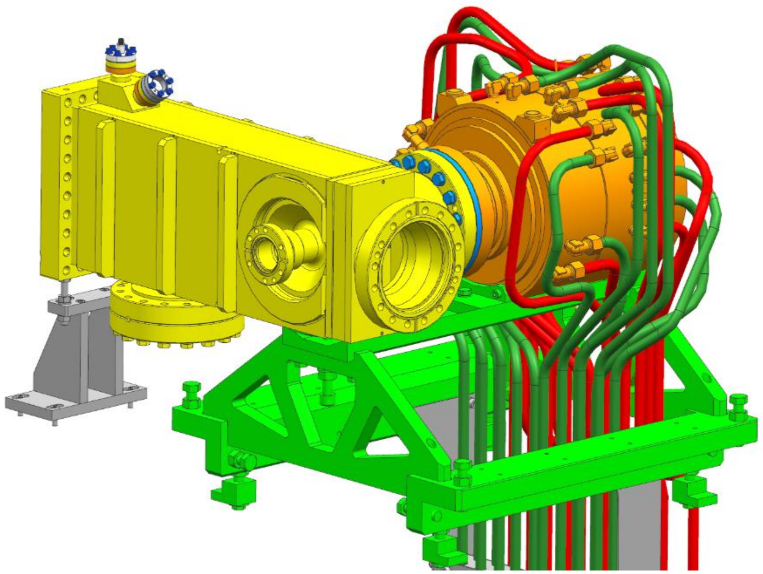
2021.02.11

Outline

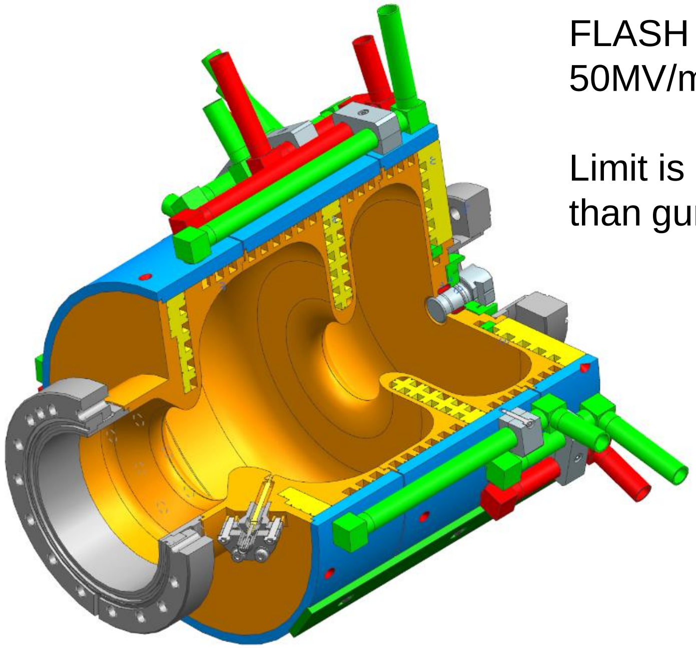
- Motivation and basic ideas
- RF simulations and beam dynamics studies with various cavity profiles
    - 1.5 cell gun
    - 2.5 cell gun
- Summary and outlook

Motivation

- Designed parameters for XFEL and FLASH
  - Gun 4: 60MV/m, 650us, 10Hz, average power loss 40kW
  - Gun 5: 60MV/m, 1ms, 10Hz, average power loss 60kW



Gun 4 in beam line



Gun 5 in fabrication process

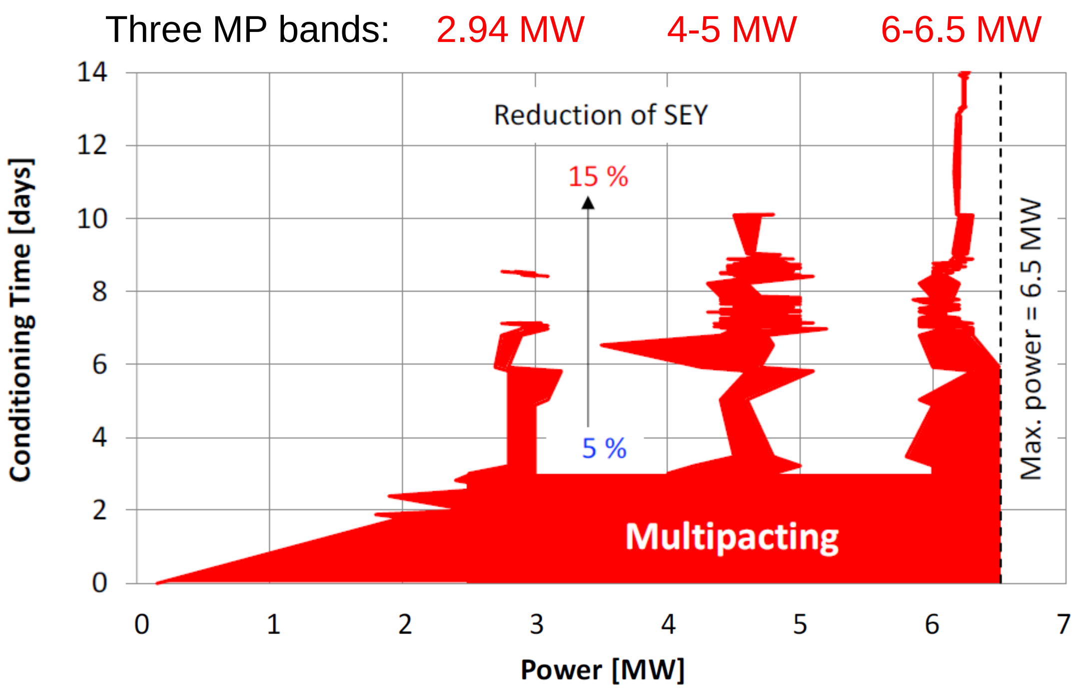
FLASH operation in future:
50MV/m, 1ms, 10Hz, 48kW

Limit is more the rf window than gun cavity.

Motivation

- How to further increase duty cycle?
  - Cooling capacity fully optimized in Gun 5
  - Cavity needs redesign → reduce power loss per cell
- How to improve operation reliability?
  - Multipacting in window vicinity and coupler→ move rf power to lower power (MP free region)
  - Average RF heating on ceramic stresses the brazed joint between the ceramic and the surrounding metal → reduce rf peak power
  - Discharge in waveguide → reduce rf peak power
  - Pulsed heating $P_d\sqrt{t}$ → reduce power loss density

A lower peak rf power and lower power loss density should be the target for a next generation L band NC pulsed gun.



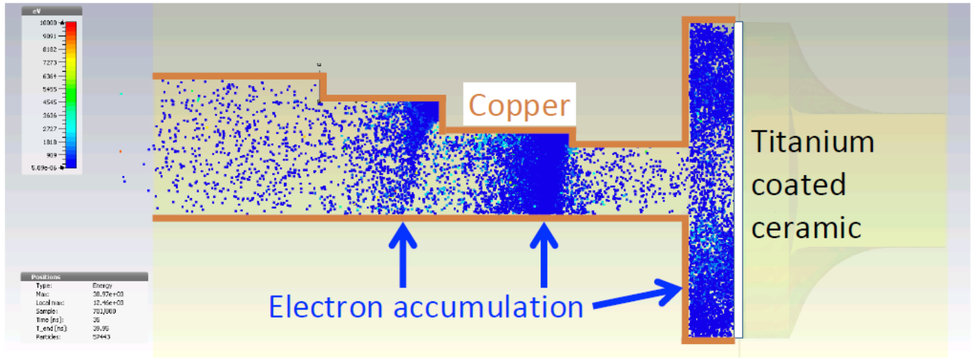


Figure 7: Typical electron distribution at the beginning of conditioning here at a power of 6.36 MW after 35 ns.

M. Bousonville, IPAC 2018, WEPMF051

Basic ideas

Shunt impendence increase

- Power loss in the gun

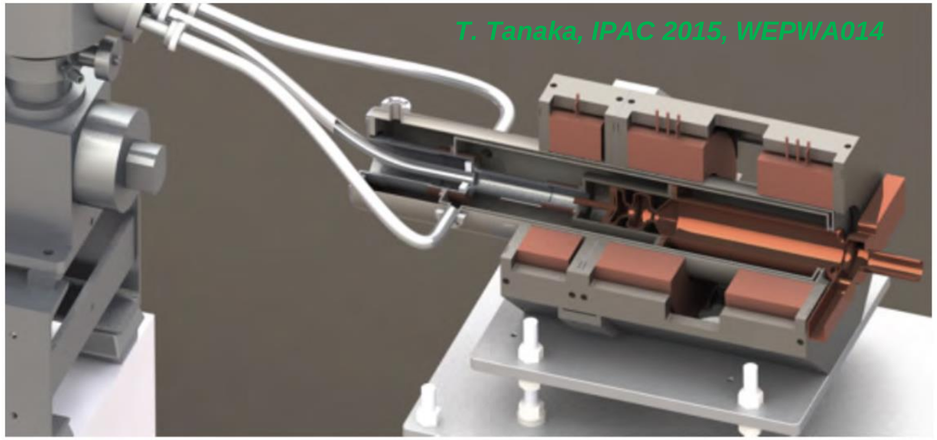
$$P_{rf} = \frac{V_{beam}^2}{R}$$

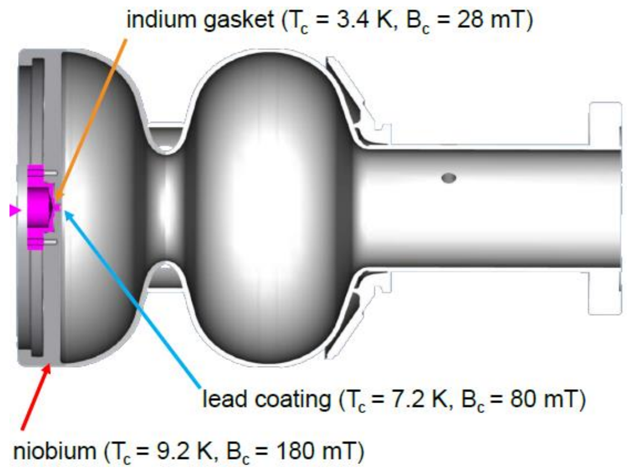
V_{beam}^2 → critical for beam performance

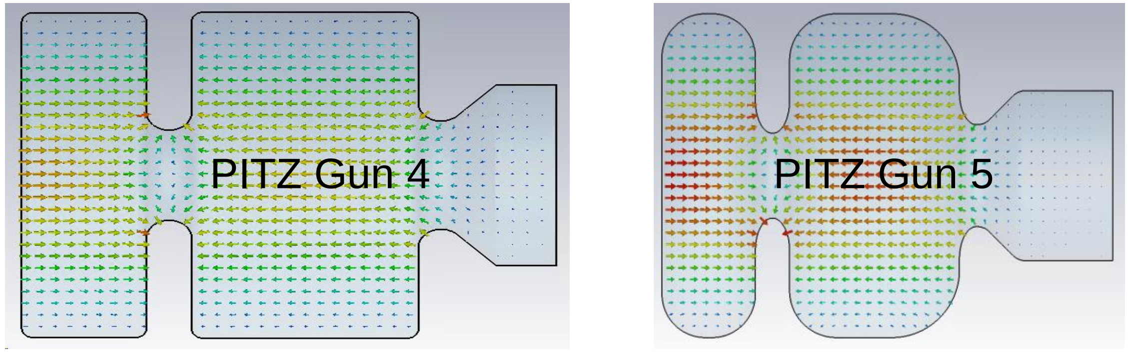
R → how to increase?

- For a fixed cavity profile, R/Q is constant, R can be increased with Q
    - Cu cavity in a cryogenic tank (20K)
    - SRF Nb cavity (Q0 $10^4 \rightarrow 10^{10}$)

- Increase R, gun cavity optimization
    - Gun4 6.29 MΩ → Gun5 6.62 MΩ, round corner reduce surface power loss
    - Nose cone increase shunt impedance
    - More cells

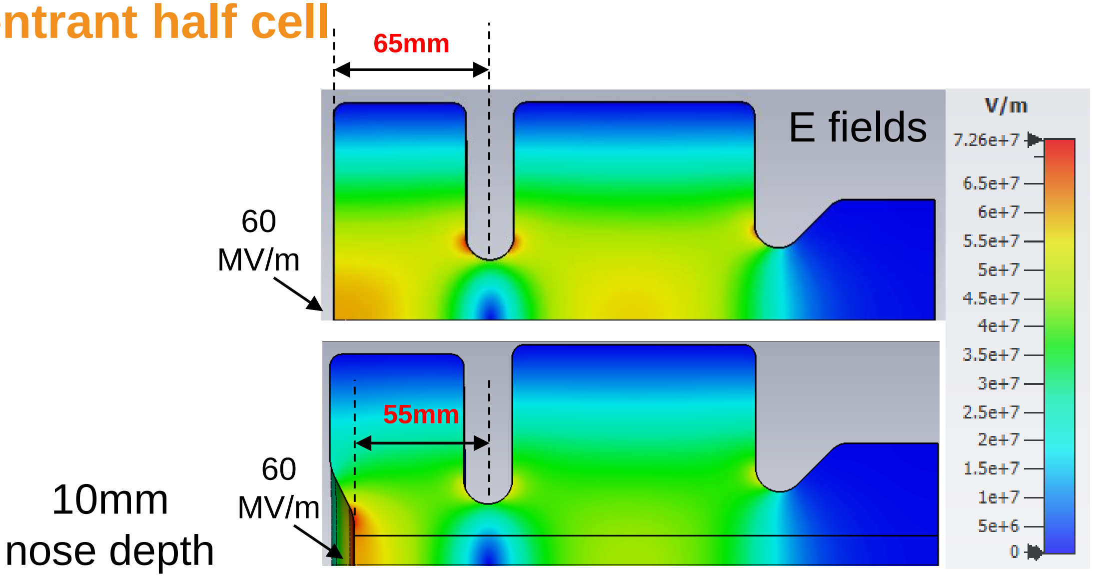


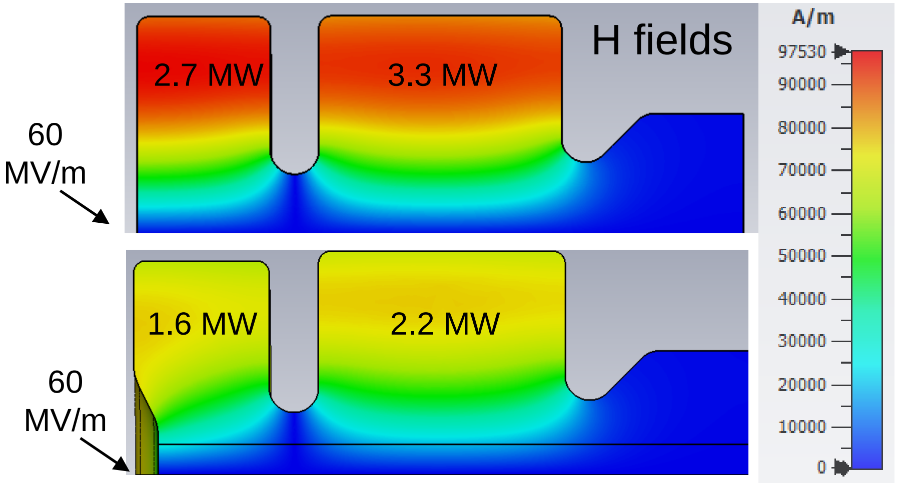


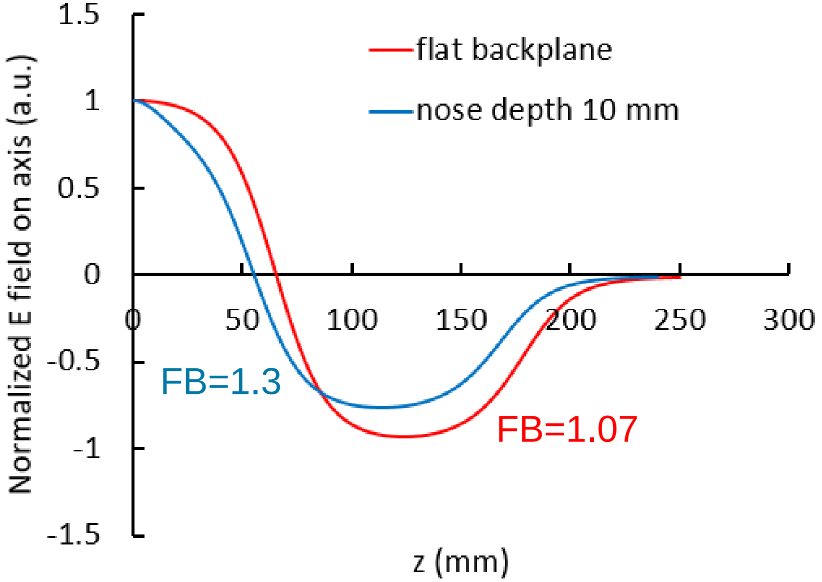


Basic ideas

Re-entrant half cell







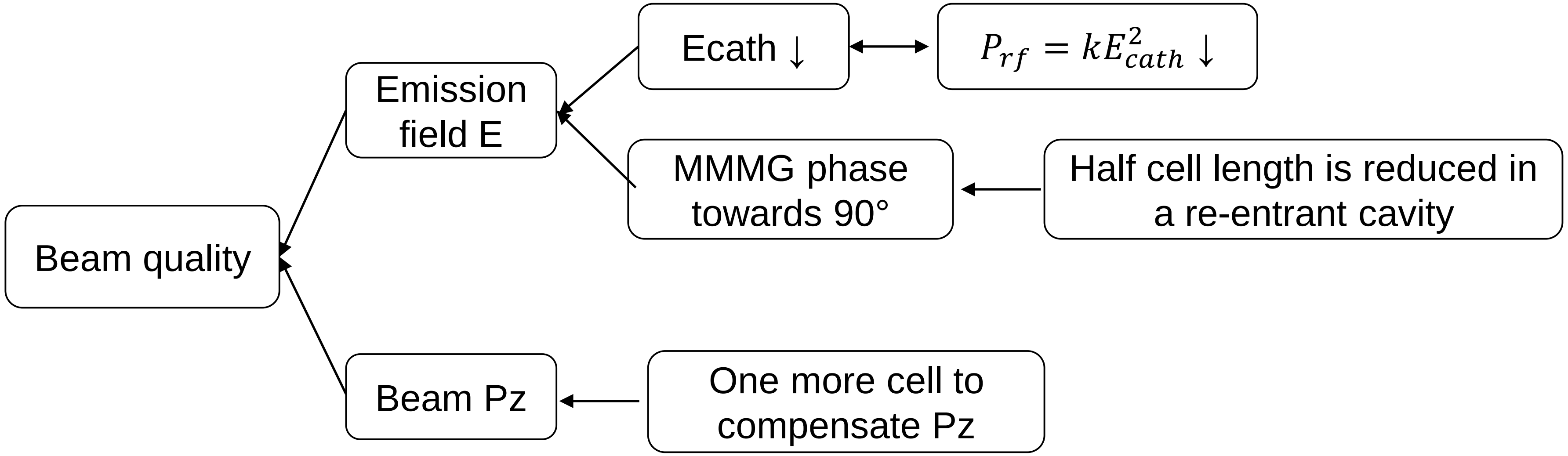
- Assume cathode gradient is constant:
  - Power loss in half and full cells reduce
  - Beam momentum reduces → booster best matching position must be moved towards cathode → space limitation due to diagnostics between gun and booster → one more cell for beam energy compensation

Basic ideas

Lower cathode gradient

- Power loss in the gun

$$P_{rf} = kE_{cath}^2$$



RF simulation and beam dynamics optimization

Definitions in beam dynamics optimization:

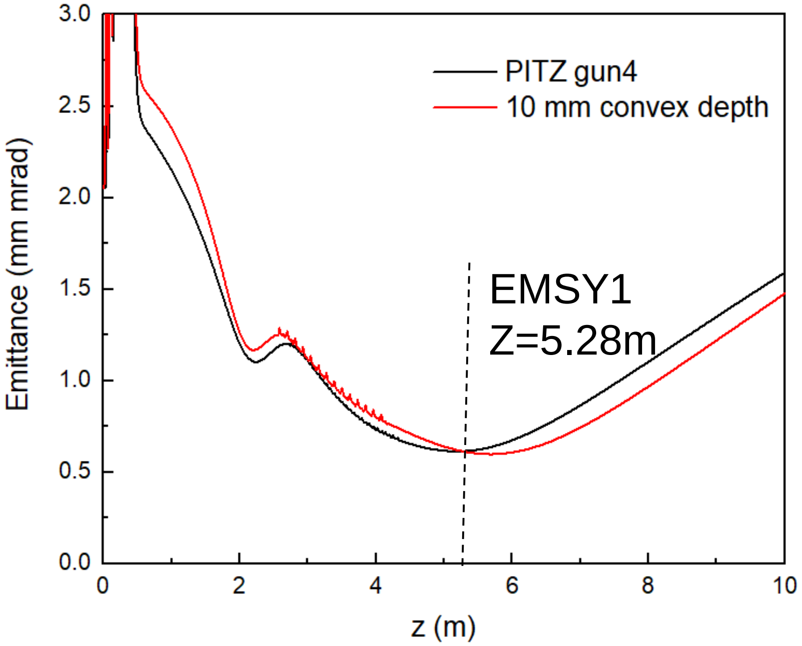
- Laser transverse homogenous; longitudinal flat top 2/21.5/2 ps
- Thermal emittance 0.847um/mm
- ASTRA + Multi-Objective Genetic Algorithm (MOGA)
  - Fixed: booster E & phase; cathode gradient
  - Variables: laser size, gun phase, solenoid Bz & position, booster position
  - Objective: minimal projected emittance at EMSY1

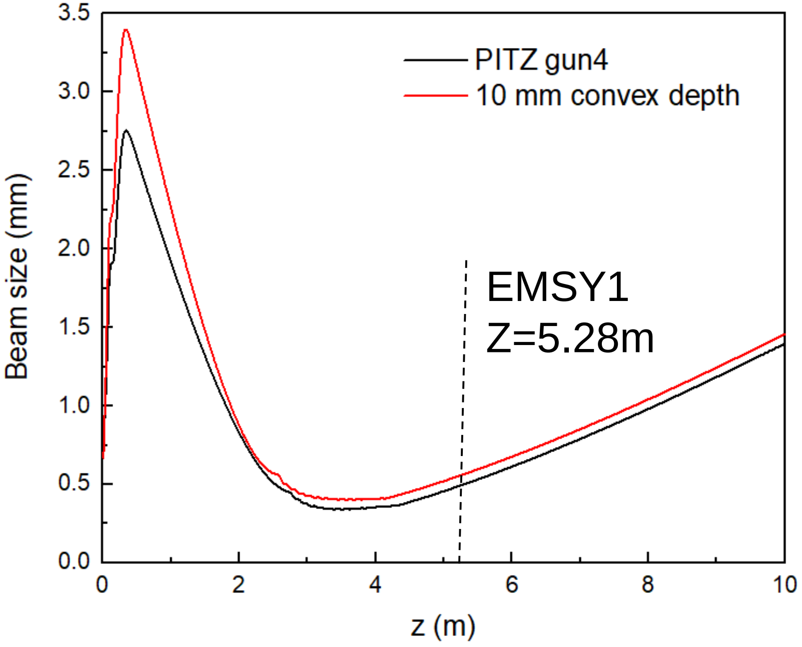
	Cavity type	PITZ 1.6 cell Gun 4	1.5 cell with 10 mm nose depth
RF properties	Ecath (MV/m)	60	60
	Field balance	1.07	1.30
	Peak power (MW)	6.03	3.76 (↓38%)
	Max. loss density (W/cm2)*	29.1	18.0 (↓38%)
Beam dynamics optimization	Charge (nC)	1	1
	MMMG phase	44.7	58.9
	Launch E (MV/m)	41.5	50.1
	Pz @MMMG (MeV/c)	6.65	5.31
	Laser rms size (mm)	0.467	0.419
	Gun phase w.r.t MMMG (deg)	-0.95	-2.16
	Solenoid position (m)	0	-0.0044
	Solenoid peak Bz(T)	-0.2289	-0.1892
	Booster position (m)	2.675	2.502
	Booster gradient (MV/m)	20	20
	Emittance at EMSY1 (um)	0.62	0.61

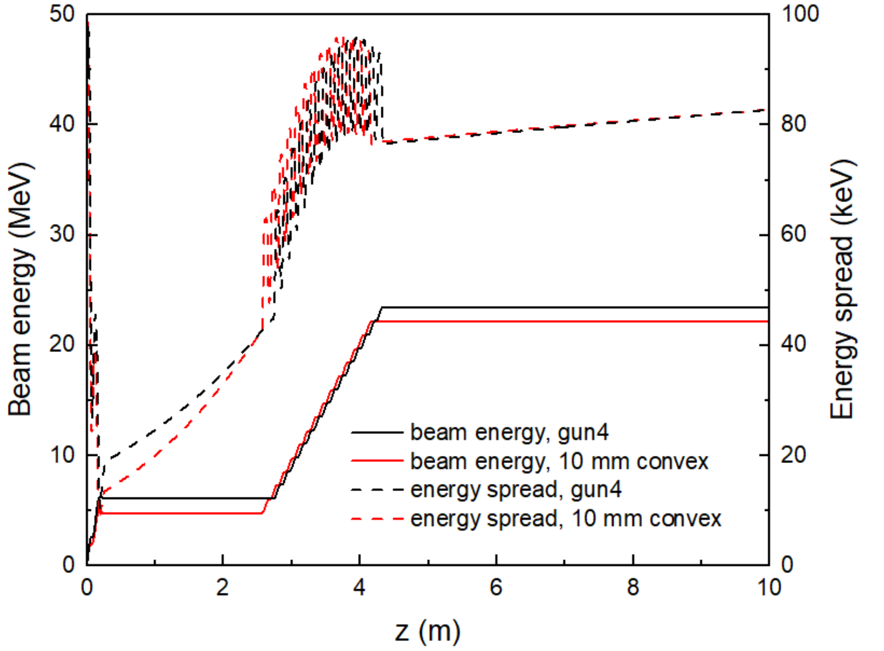
Booster moved towards cathode by 17 cm

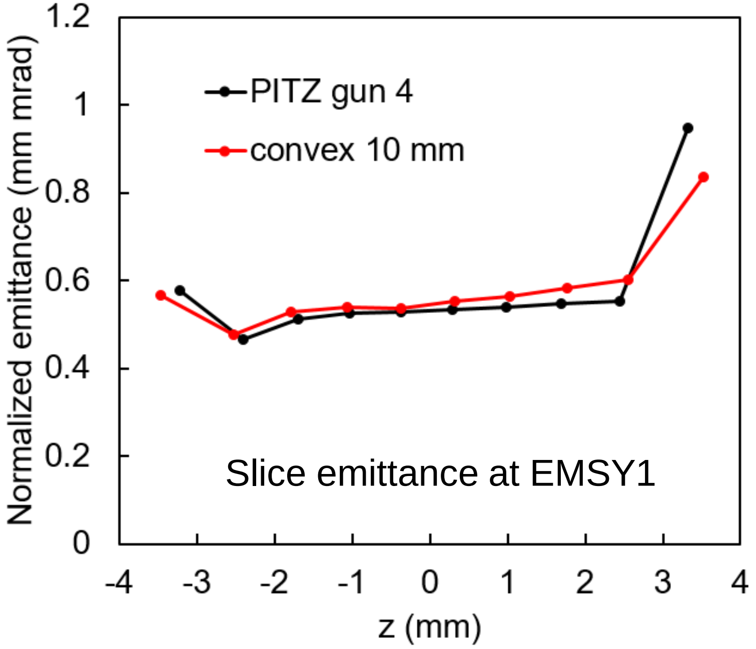
* Take duty factor 650us & 10Hz in to account

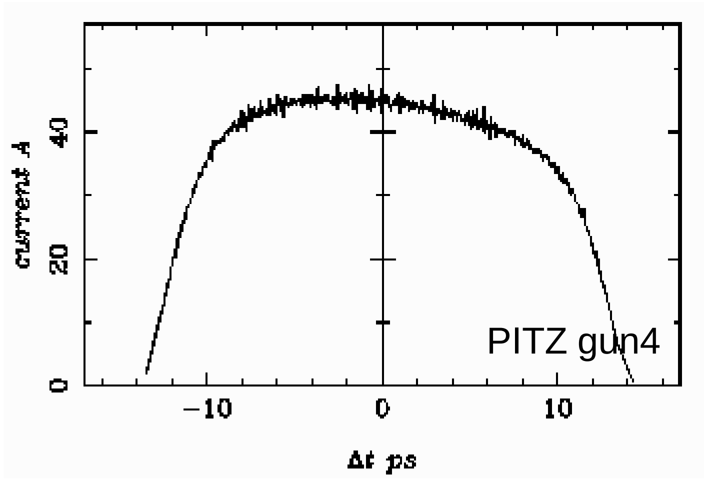
Beam parameter evolutions along beam line (Q=1nC)

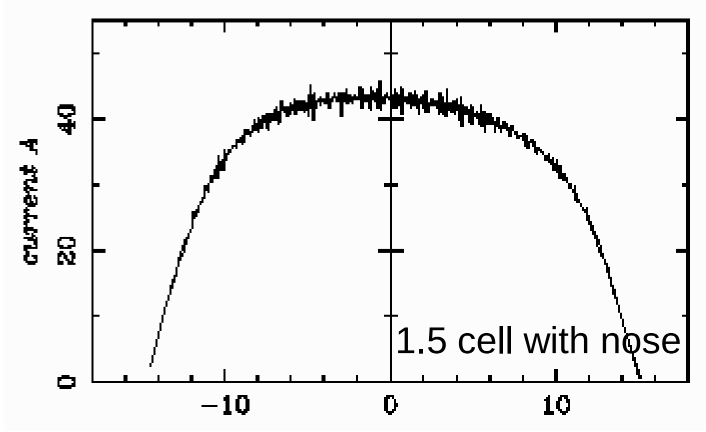






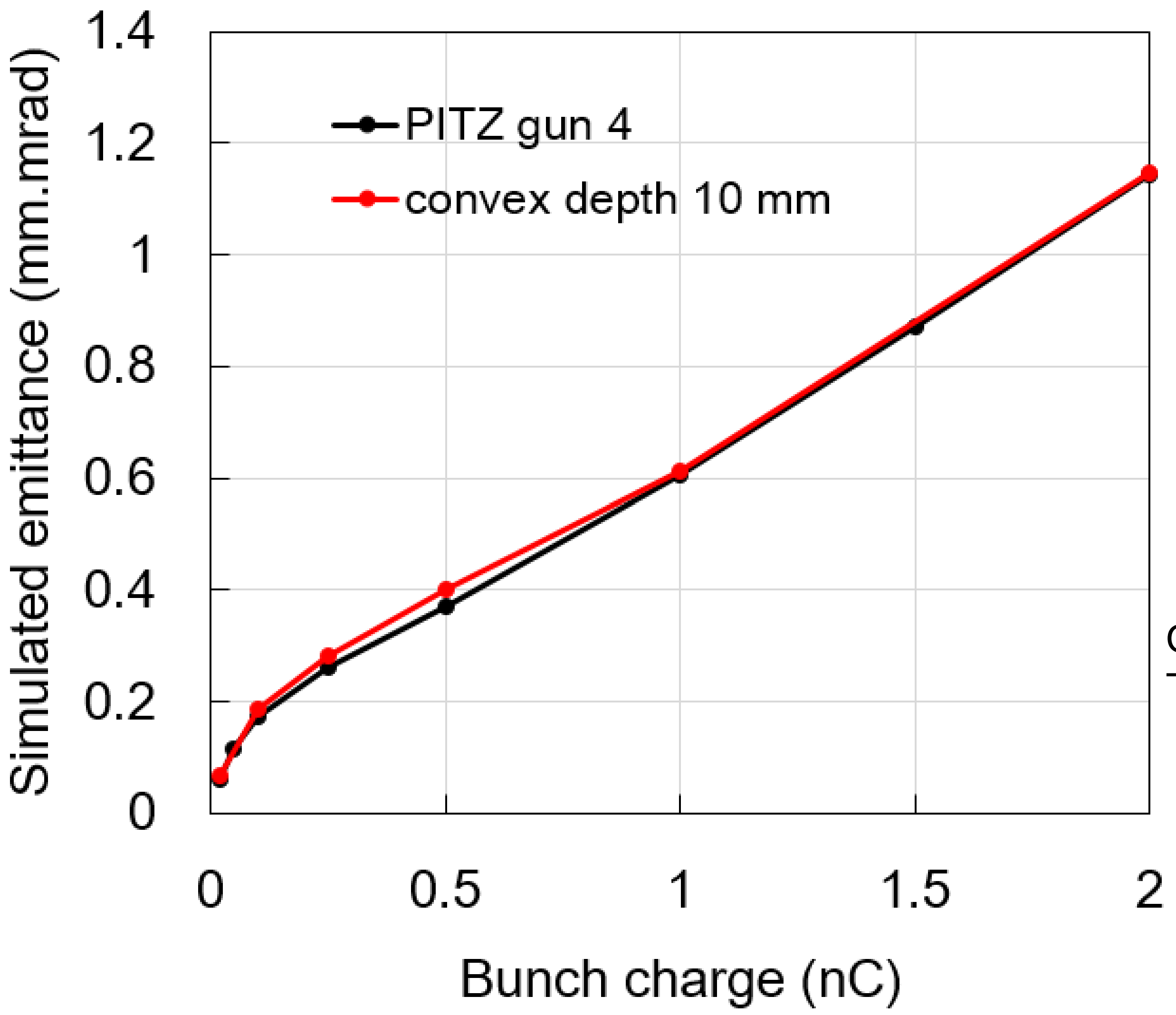






Beam current at EMSY1

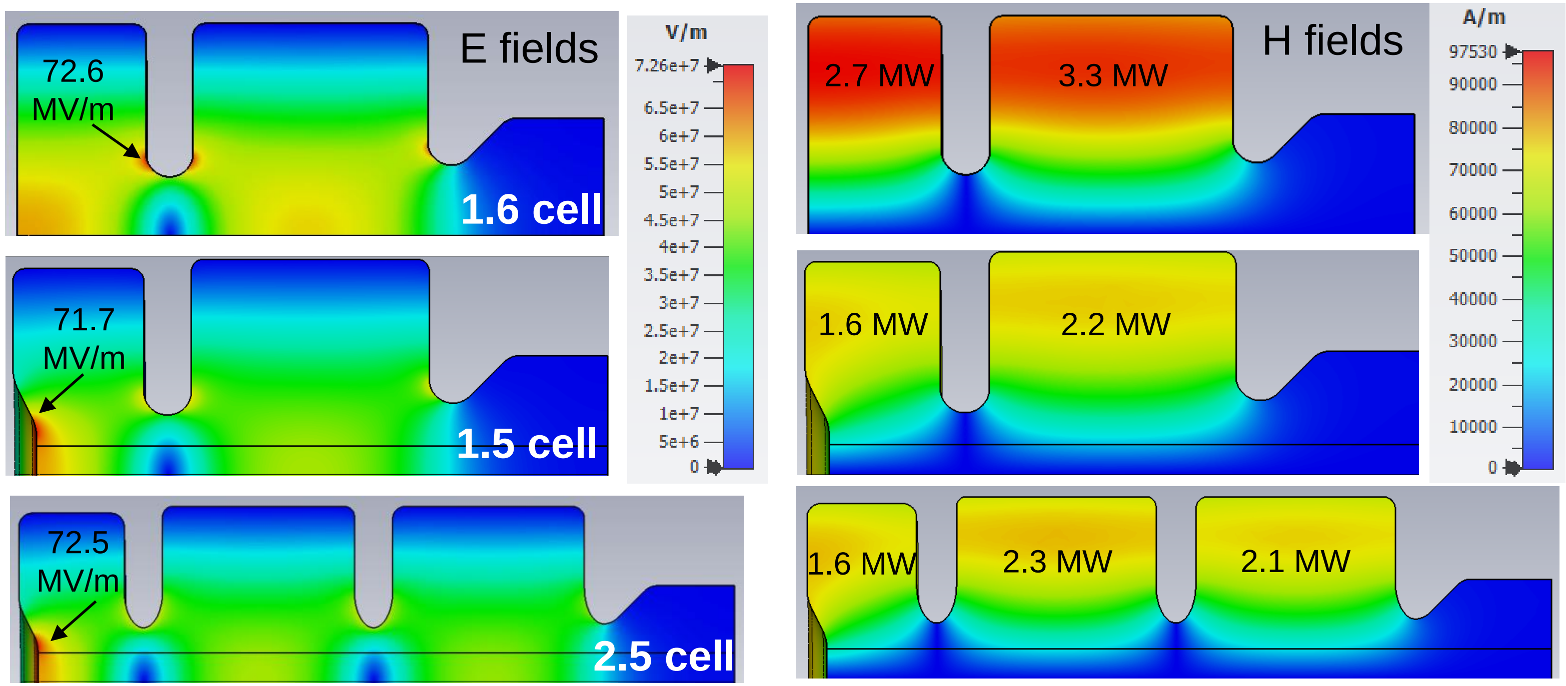
Emittance vs. bunch charge



Gun 4 raw data from Mikhail.
TUOANO04 FEL2013.

One more cell for Pz compensation

Cathode E = 60 MV/m

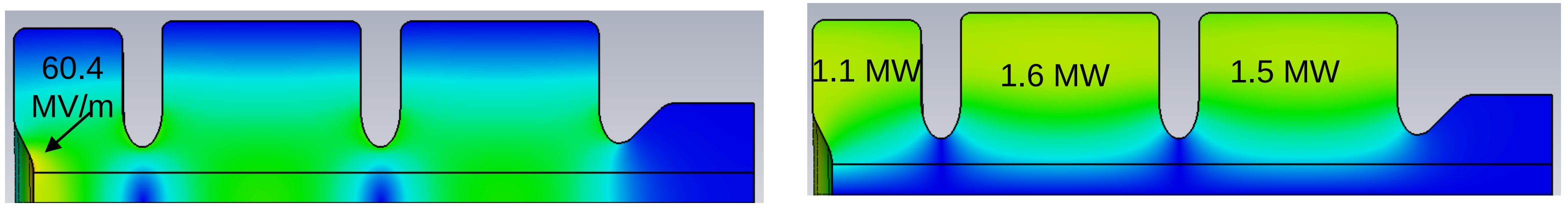


Pz=6.7 MeV/c

Pz=5.3 MeV/c

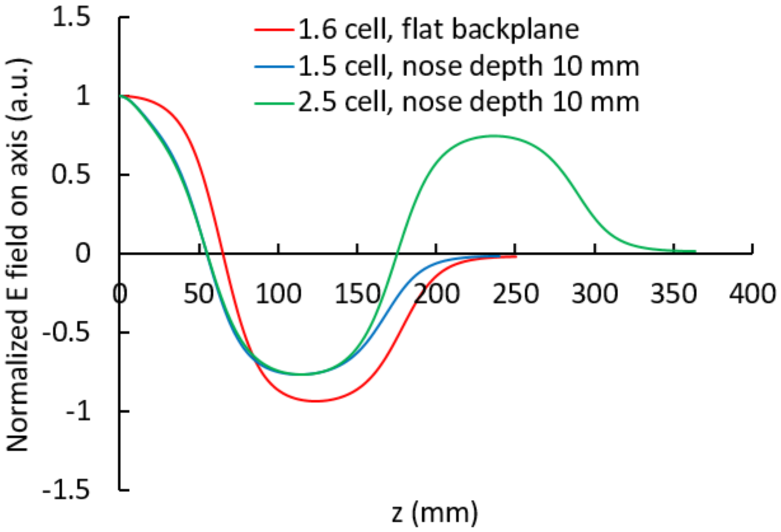
Pz=8.1 MeV/c

Cathode E = 50 MV/m



Pz=6.8 MeV/c

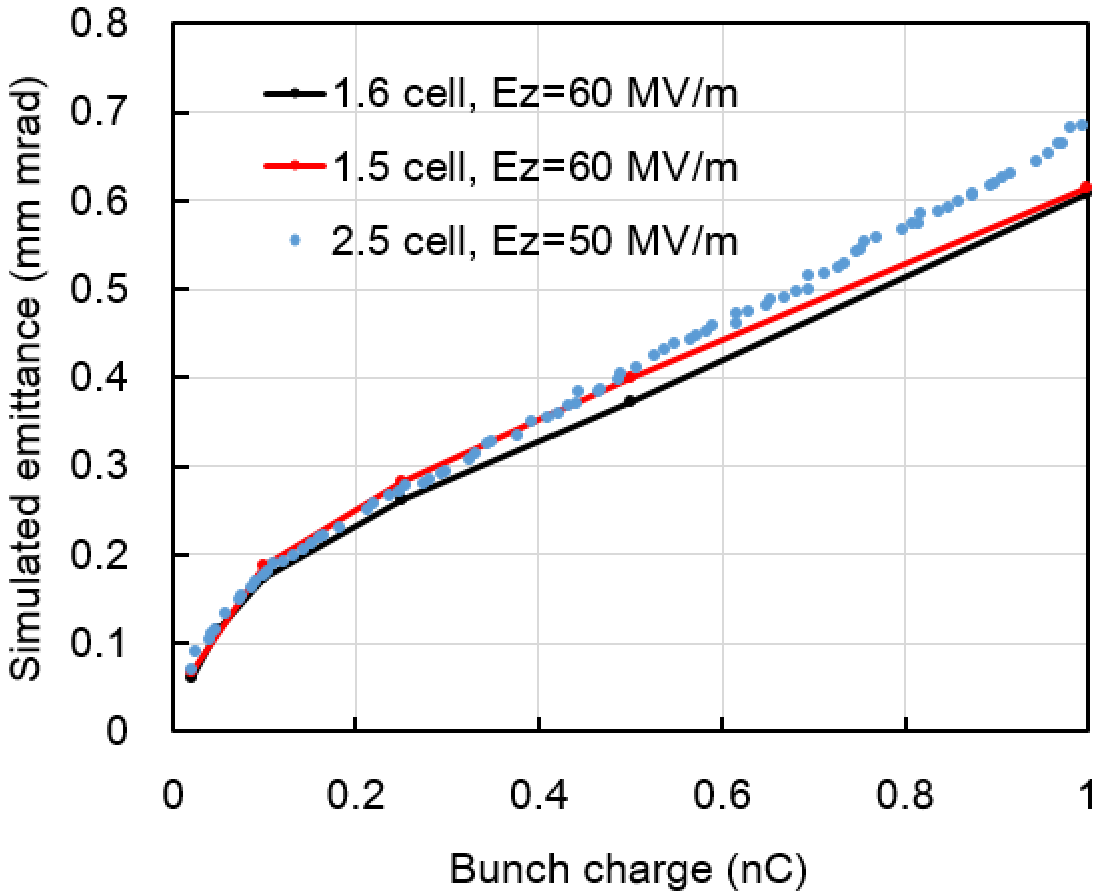
1.5 cell → 2.5 cell
Iris diameter is increased by 6mm to maintain similar mode separation ~5MHz



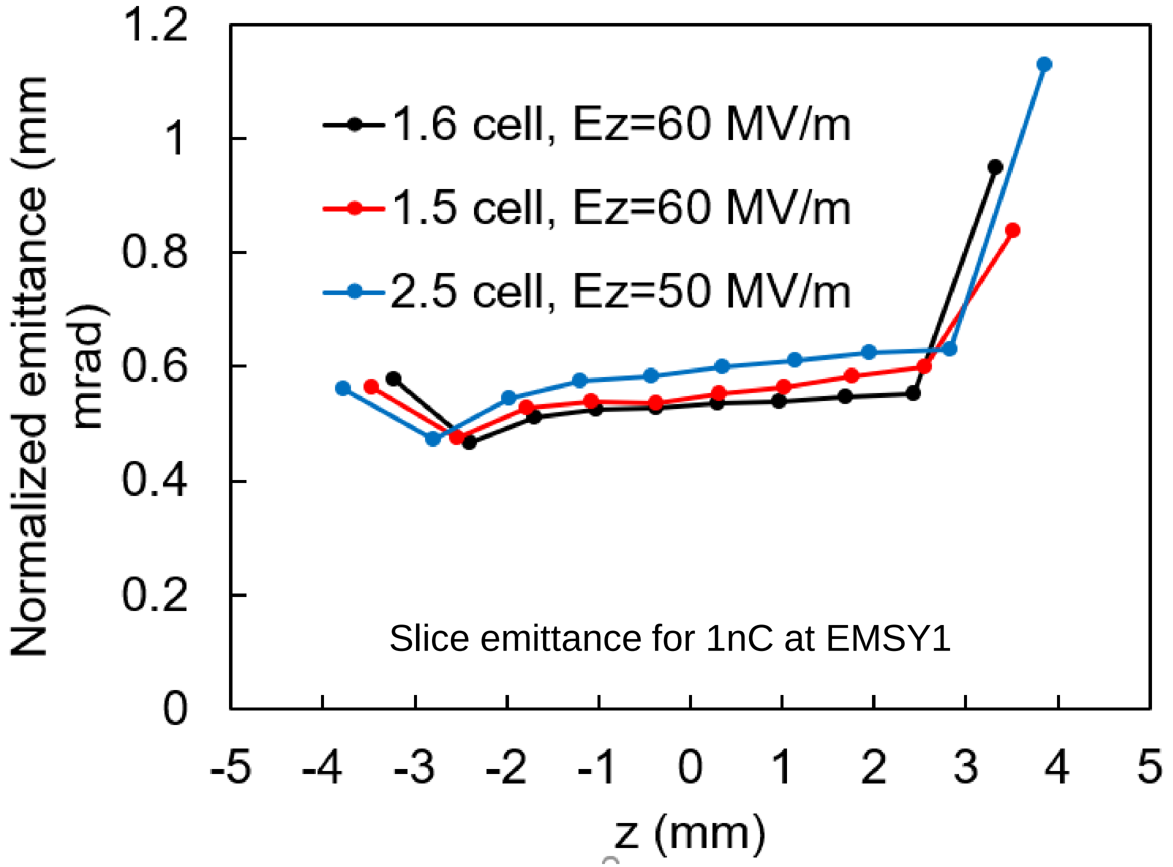
RF simulation and beam dynamics optimization

	Cavity type	PITZ 1.6cell Gun 4	1.5 cell with 10 mm nose depth	2.5 cell with 10 mm nose depth	2.5 cell with 10 mm nose depth
RF properties	Ecath (MV/m)	60	60	60	50
	Field balance	1.07	1.30	1.30	1.30
	Peak power (MW)	6.03	3.76 (↓38%)	6.09 (↑1%)	4.23 (↓30%))
	Max. loss density (W/cm2)	29.1	18.0 (↓38%)	18.8 (↓35%)	13.0 (↓55%)
Beam dynamics optimization	Charge (nC)	1	1	1	1
	MMMG phase	44.7	58.9	61.3	58.1
	Launch E (MV/m)	41.5	50.1	54.0	42.5
	Pz @MMMG (MeV/c)	6.65	5.31	8.09	6.81
	Laser rms size (mm)	0.467	0.419	0.348	0.425
	Gun phase w.r.t MMMG (deg)	-0.95	-2.16	2.76	2.12
	Solenoid position (m)	0	-0.0044	-0.0035	-0.0066
	Solenoid peak Bz(T)	-0.2289	-0.1892	-0.2341	-0.1999
	Booster position (m)	2.675	2.502	3.518	3.129
	Booster gradient (MV/m)	20	20	20	20
	Emittance at EMSY1 (um)	0.62	0.61	0.62	0.72

Emittance vs. bunch charge



1.6 cell Gun 4 raw data from
Mikhail. TUOANO04 FEL2013.



Conclusion and outlook

- Main features of the new gun with a nose cone
  - Reentrant cathode cell
    - enhanced cathode field
    - shunt impedance increase
  - 1.5 cell, 60 MV/m cathode E
    - similar dynamics
    - lower peak power (3.8MW), 1 ms x 10 Hz (38 kW), better reliability
    - minimum change to existing fabrication and tuning technique
    - lower Pz (5.3MeV/c), beam line space limitation?
  - 2.5 cell, 50 MV/m cathode E
    - similar dynamics
    - lower peak power (4.2MW), 1 ms x 20 Hz (85 kW, same power per cell as gun5), challenge?
    - same Pz (6.8MeV/c)

- Outlook
  - Preliminary thermal analysis with gun-5 type cooling
  - Further optimizations of reentrant cell and other cells
  - Dark current tracking analysis
  - Prepare a IPAC2021 paper

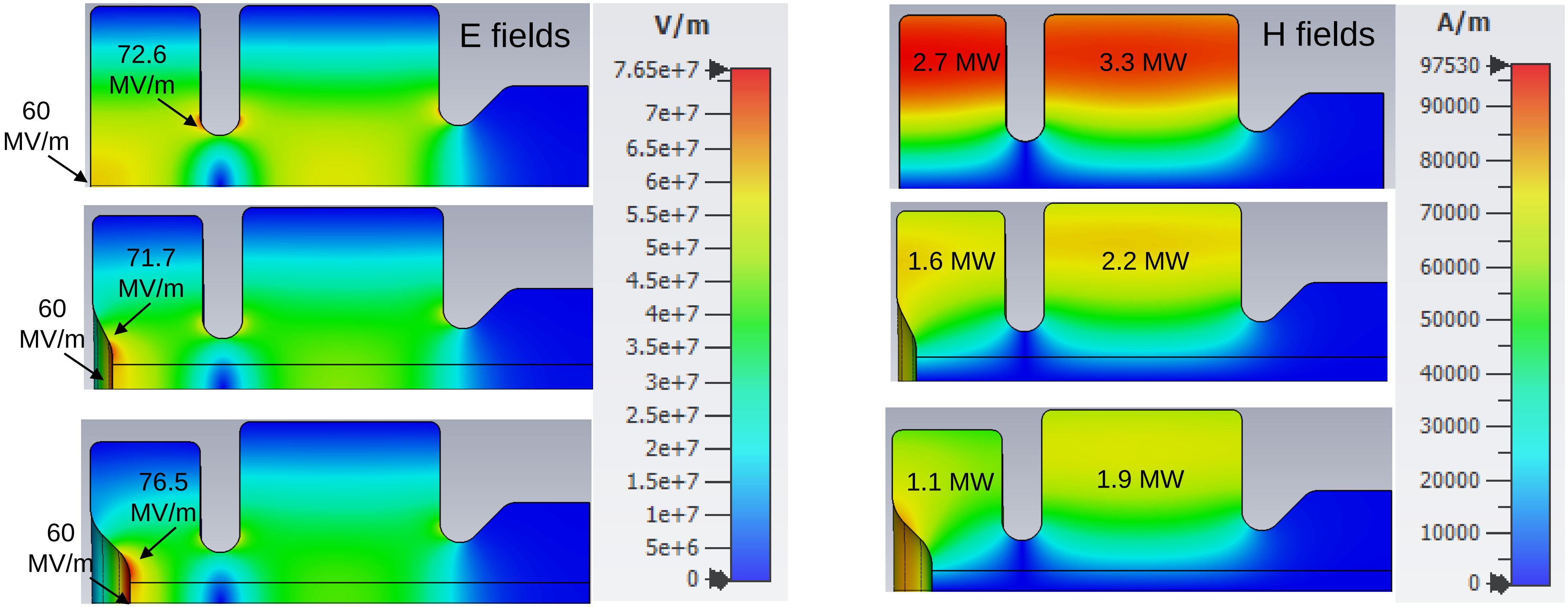
Thanks for your attention.

What convex depth should be chosen?

Depth =0mm

Depth =10mm

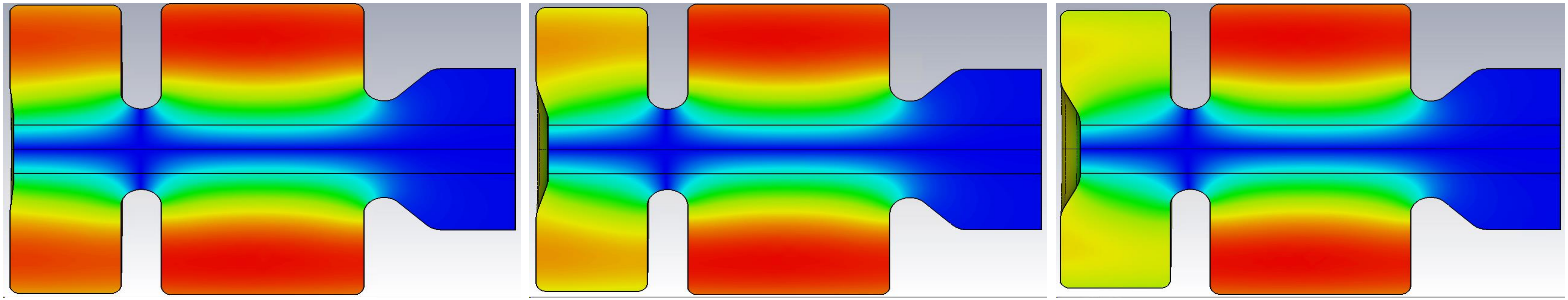
Depth =20mm



With a larger depth:

- RF power required is lower (6.0MW → 3.8MW → 3.0MW)
- E field enhancement on nose is stronger, breakdown and dark current ,radiation dose…
- Power loss density homogeneity in half cell is worse, heat concentrates near nose cone
- A dedicated cooling for nose might be required, make cooling channel more complicate

Backup slides



Field balance =1