SHORT-PULSE X-BAND PHOTOGUN: FROM FIRST DEMONSTRATION TO RECENT RESULTS & FUTURE DEVELOPMENTS

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07/27/2026

U.S. DEPARTMENT of ENERGY
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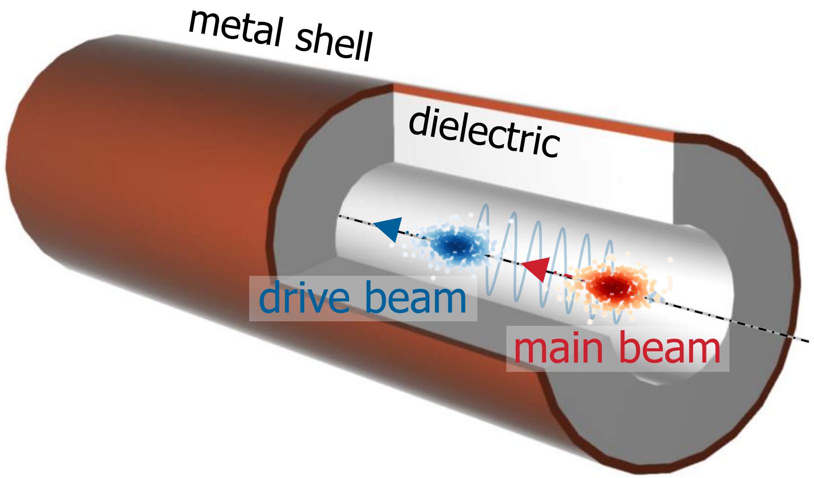
OUTLINE

- **Introduction** to Structure wakefield acceleration (SWFA)
- **Two beam acceleration (TBA)** at Argonne Wakefield Acceleration (AWA) facility
- **Motivation** for short-pulse acceleration
- **Selected highlights** of the X-band photogun (Xgun):
  - Phase scans @ different gradients
  - Understanding of the short-pulse operation and beam performance
  - Longitudinal phase space (recent work)
- **Future developments**

STRUCTURE WAKEFIELD ACCELERATION

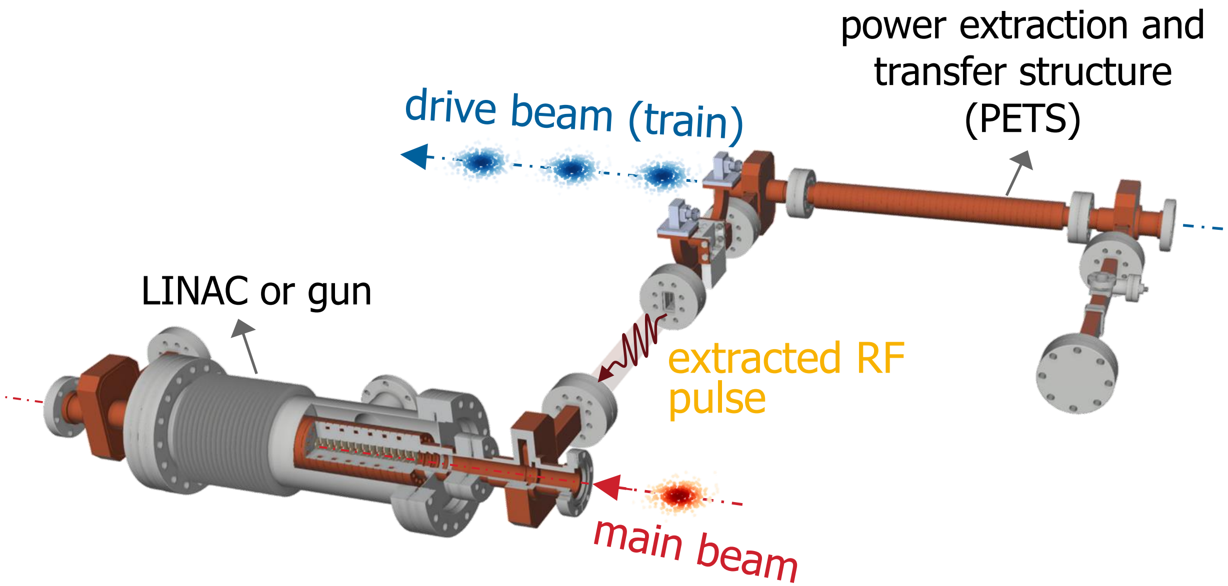
CWA and TBA

Collinear Wakefield Acceleration (CWA)



- Drive and main beam propagate in the same structure.
- Energy is transferred locally from the wakefields of the leading bunch to a trailing bunch.

Two Beam Acceleration (TBA)



- Drive and main beams propagate in separate beamlines and different structures.
- RF power is extracted from the drive beam and transferred to the main beamline.

TWO BEAM ACCELERATION (TBA)

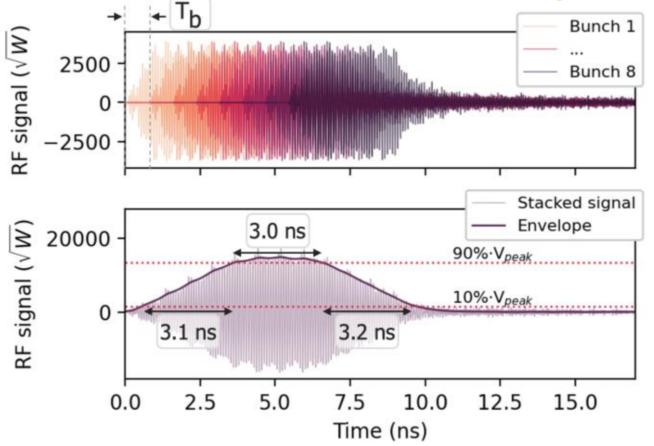
A single TBA module

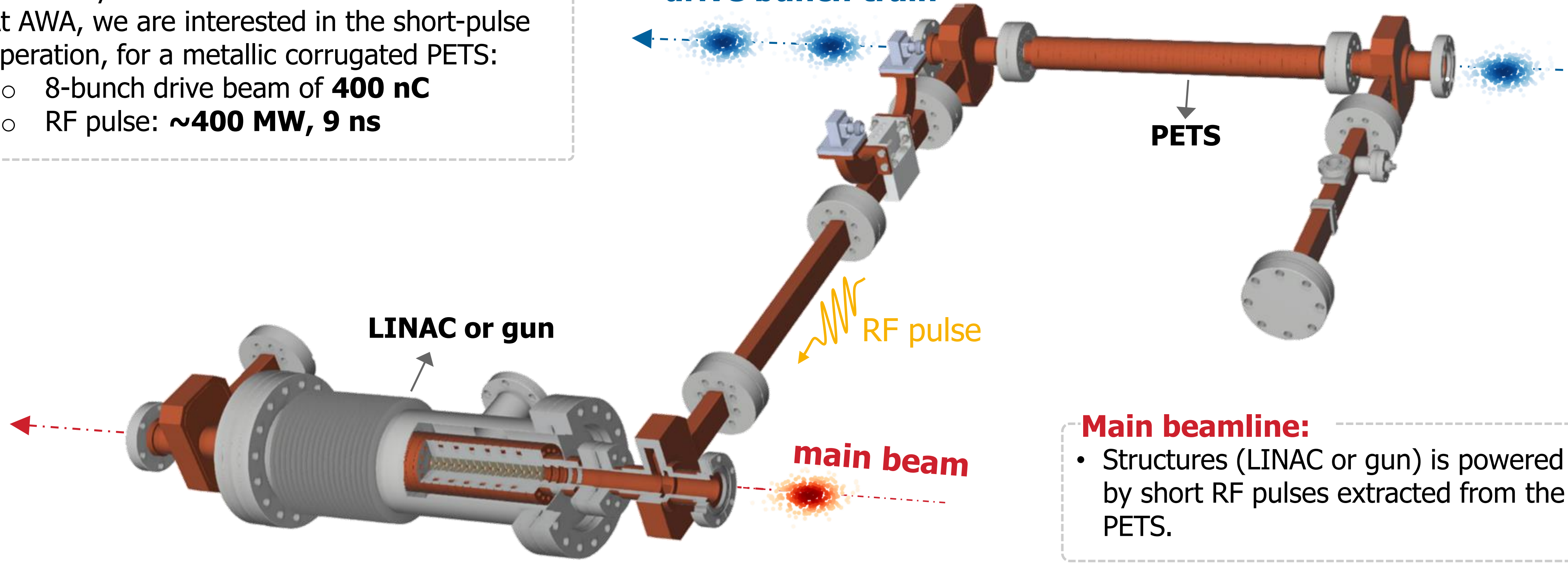
Drive beamline:

Principle: coherent stacking of wakefield pulse produced by each bunch within a train.

- At AWA, we are interested in the short-pulse operation, for a metallic corrugated PETS:
  - 8-bunch drive beam of **400 nC**
  - RF pulse: **~400 MW, 9 ns**

Simulated RF pulse



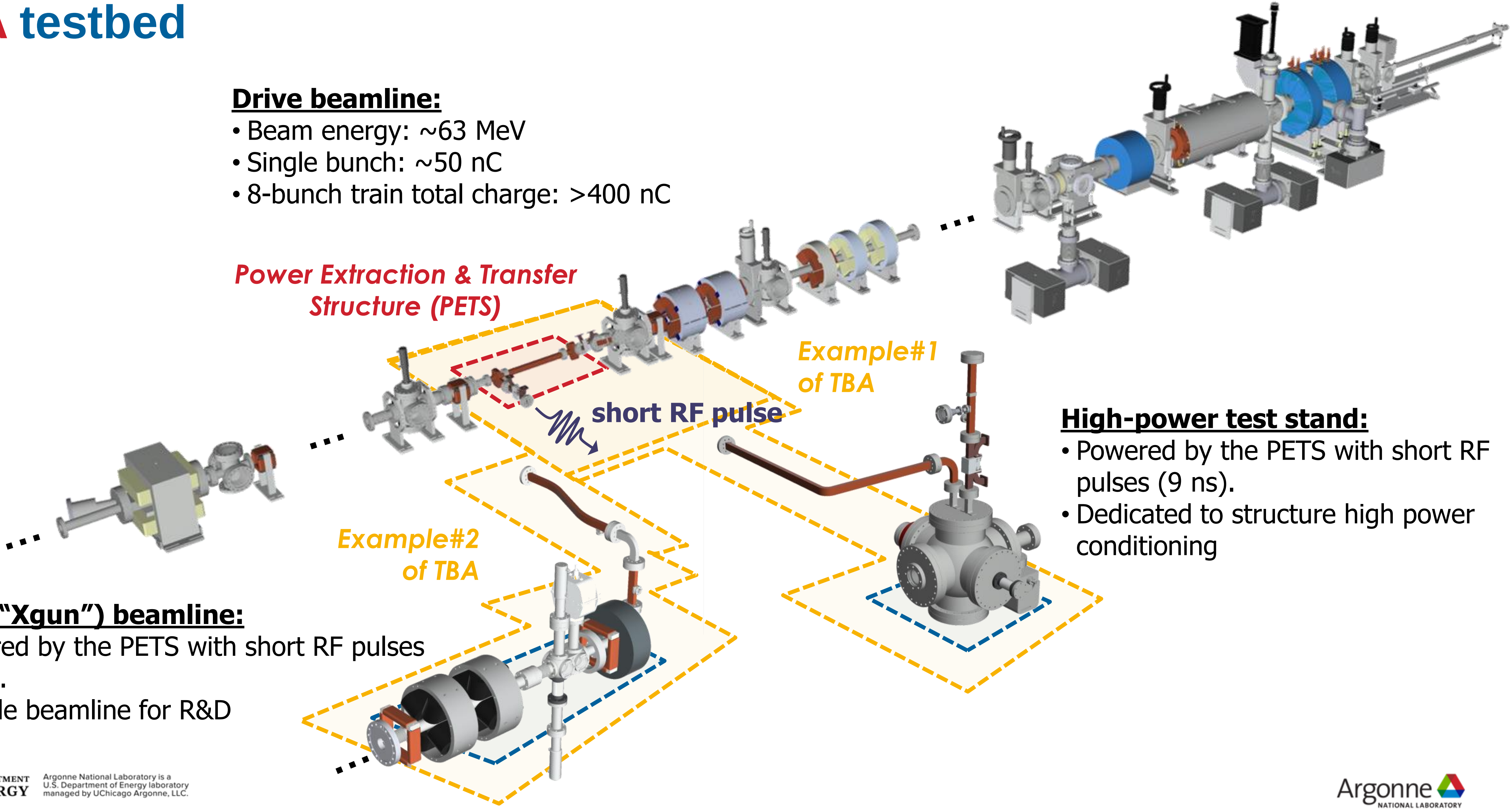


Main beamline:

- Structures (LINAC or gun) is powered by short RF pulses extracted from the PETS.

AWA TEST FACILITIES

TBA testbed



Drive beamline:
- Beam energy: ~63 MeV
- Single bunch: ~50 nC
- 8-bunch train total charge: >400 nC

High-power test stand:
- Powered by the PETS with short RF pulses (9 ns).
- Dedicated to structure high power conditioning

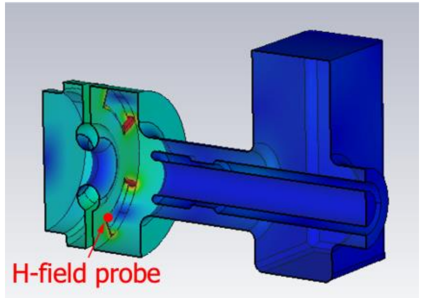
Main ("Xgun") beamline:
- Powered by the PETS with short RF pulses (9 ns).
- Flexible beamline for R&D

Why Short-pulse?

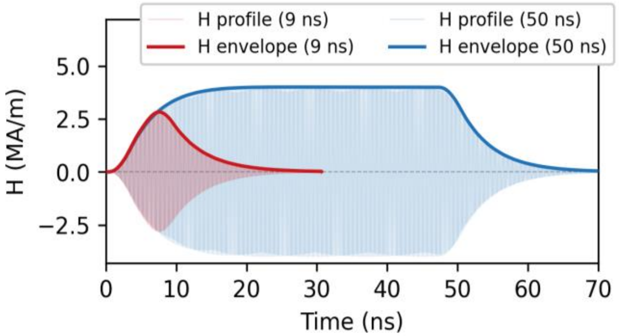
Motivation

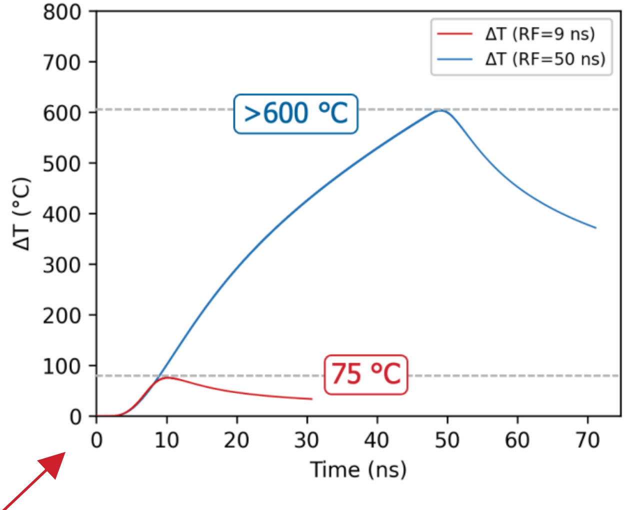
- ❖ Achieved >400 MV/m in an X-band photogun with a low breakdown rate under short-pulse operation.

Pulsed heating: high H-field induced temperature rise



Monitor local H-field evolution

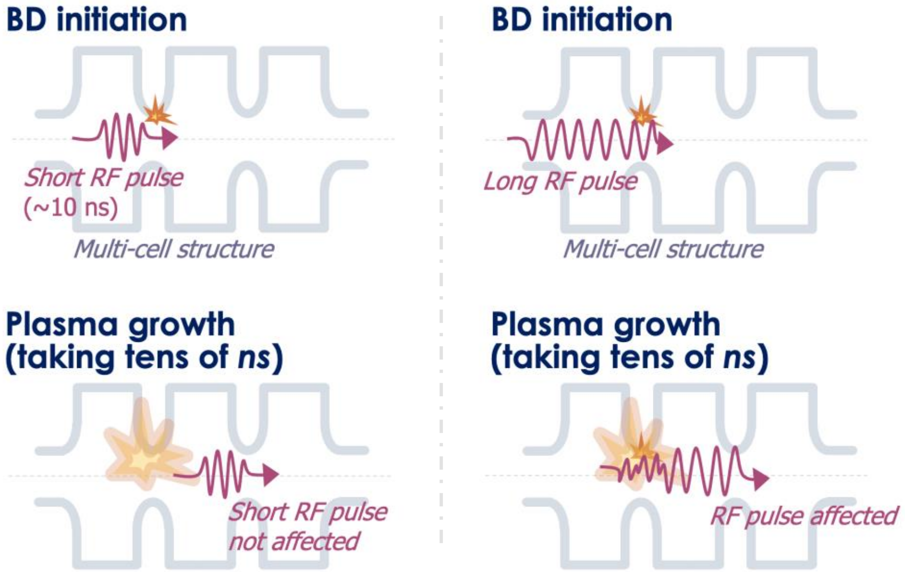




- Equation: $\Delta T \propto H^2\sqrt{t_{rf}}$
- Under short pulse regime, highest temperature is ~75 °C, greatly lower than long pulse powered structure.

Breakdown insensitive acc. regime (hypothesis):

Short Pulse vs. Long Pulse



- If BD initiates plasma, the short RF pulse may transmit through the structure and remain largely unaffected [1, 2]

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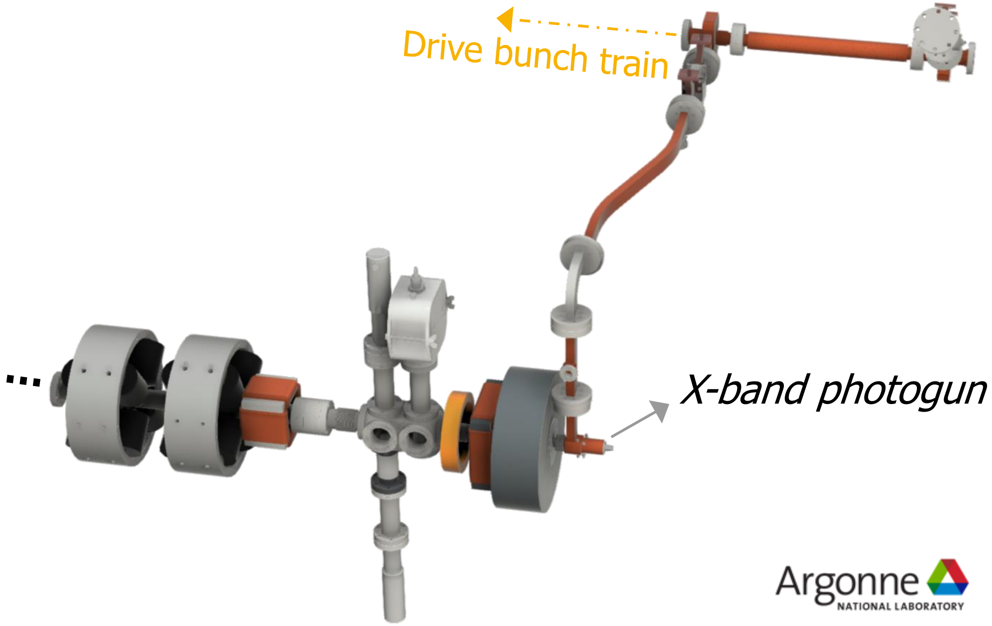
[1] J. Shao et al., IPAC2022, doi: 10.18429/JACOW-IPAC2022-FROXSP2.
[2] D. Merenich et al., Phys. Rev. Accel. Beams, vol. 27, no. 4, p. 041301, Apr. 2024

SELECTED HIGHLIGHT I:
PHASE SCANS AT DIFFERENT GRADIENTS

- Measured phase scans (charge vs. Xgun launching phase) @ different gradients: 60 MV/m to 320 MV/m
- Simulation benchmarking



PHOTOEMISSION STUDIES

Phase scans (or Schottky studies)

Simulation setup

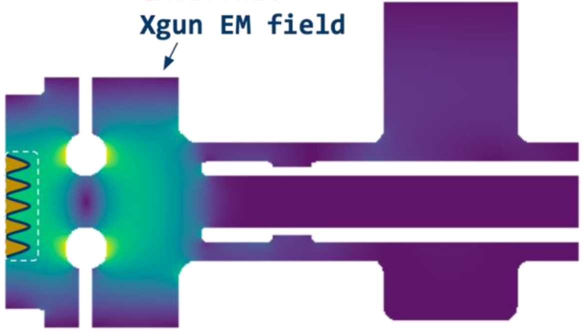
In ASTRA, bunch charge is evaluated as follows,

$$\boldsymbol{Q = Q_0 + S_1 \cdot \sqrt{E} + S_2 \cdot E}$$

where,

S_1, S_2: Schottky strength coefficients

E: field on the cathode



CAVITY#1: Xgun EM field

"CAVITY#2": EM field introduced by the surface roughness

Possible field ($\boldsymbol{E}$) contributions acting on the cathode:

$$\boldsymbol{E_{total} = \boxed{E_0 \cdot sin(\varphi_{rf}) + E_{sc}} + \boxed{E_{roughness}}}$$

Both included in ASTRA

Modeled separately using a sinusoidal surface [1-2]

where,

$E_0 \cdot sin(\varphi_{rf})$: applied rf field

E_{sc}: space charge shielding field

$E_{roughness}$: modeled 3D EM field introduced by surface roughness.

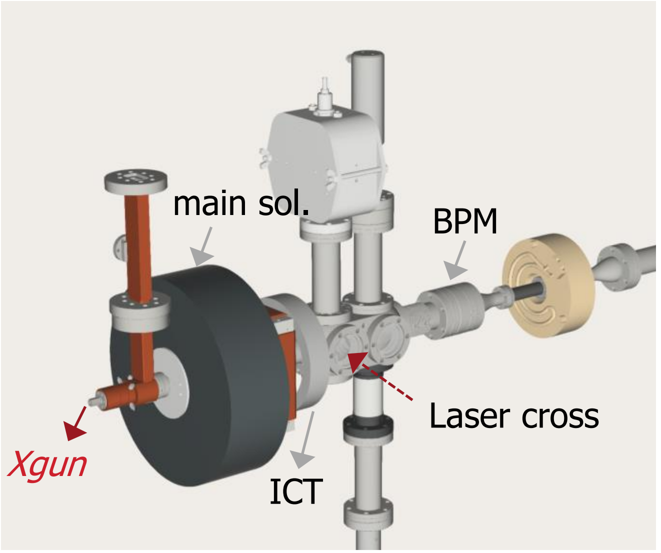


Table 1: List of the simulation parameters in ASTRA

Parameter	Value
Laser $\sigma_{x,y}$	0.5 mm
Laser pulse length, FWHM	300 fs
Laser energy	4.73 eV
Gradient on cathode	60 MV/m to 320 MV/m
Est. inital bunch charge*	5.7 pC
Est. SRT_Q_Schottky*	0.003
Est. Q_Schottky*	0
a**	0.4 μm
p**	$2\pi/50\ \mu m^{-1}$

* Parameters optimized and used in all simulations.

** Parameters in the sinusoidal function for roughness modeling, where z=a·cos(px)

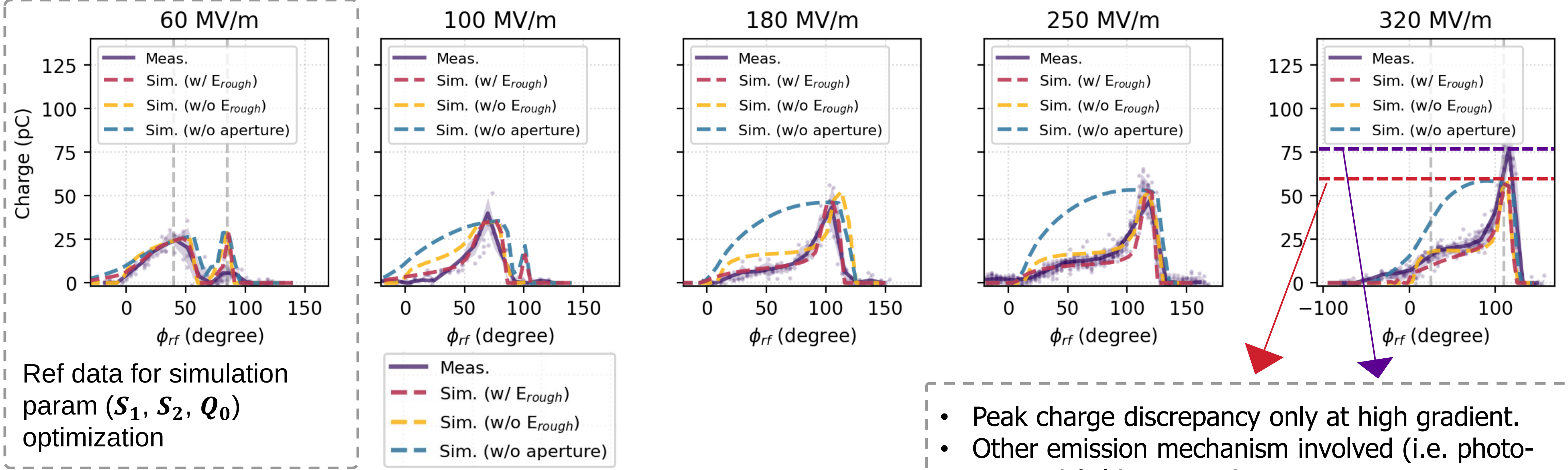
[1] D. J. Bradley, et al., J. Phys. D: Appl. Phys., Vol. 10, (1977).
[2] G. S. Gevorkyan, et al., Phys. Rev. Accel. Beams 21, 093401 (2018).

SCHOTTKY SCANS

@ 60, 100, 180, 250, 320 MV/m

In ASTRA, bunch charge is evaluated as follows,

$$Q = Q_0 + S_1 \cdot \sqrt{E} + S_2 \cdot E$$



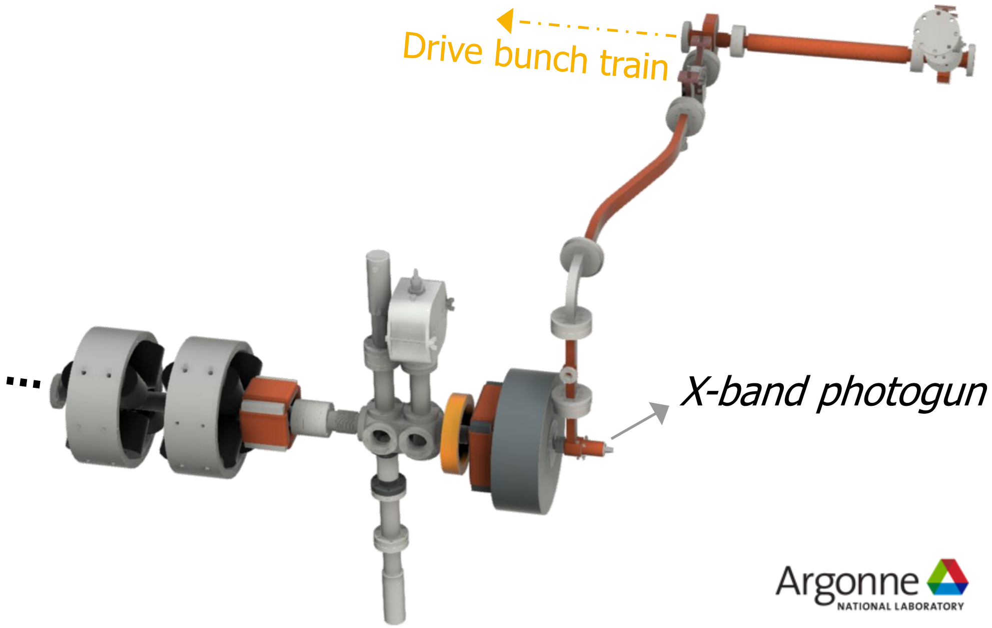
Ref data for simulation param (S_1, S_2, Q_0) optimization

- Peak charge discrepancy only at high gradient.
- Other emission mechanism involved (i.e. photo-assisted field emission)?

- At all gradients, simulations include the $E_{roughness}$ shows a better agreement with the measurements.
- Revealed a beam clipping issue at the Xgun exit.
- Photo-assisted field emission might happen at high gradient.

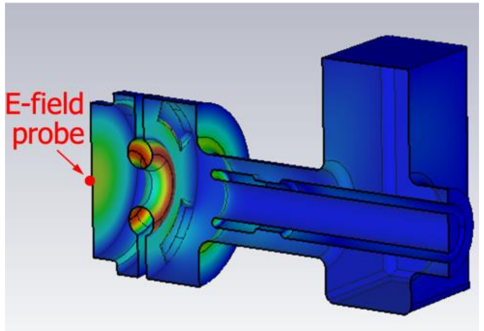
SELECTED HIGHLIGHT II:
OPERATE THE XGUN IN TRANSIENT REGIME

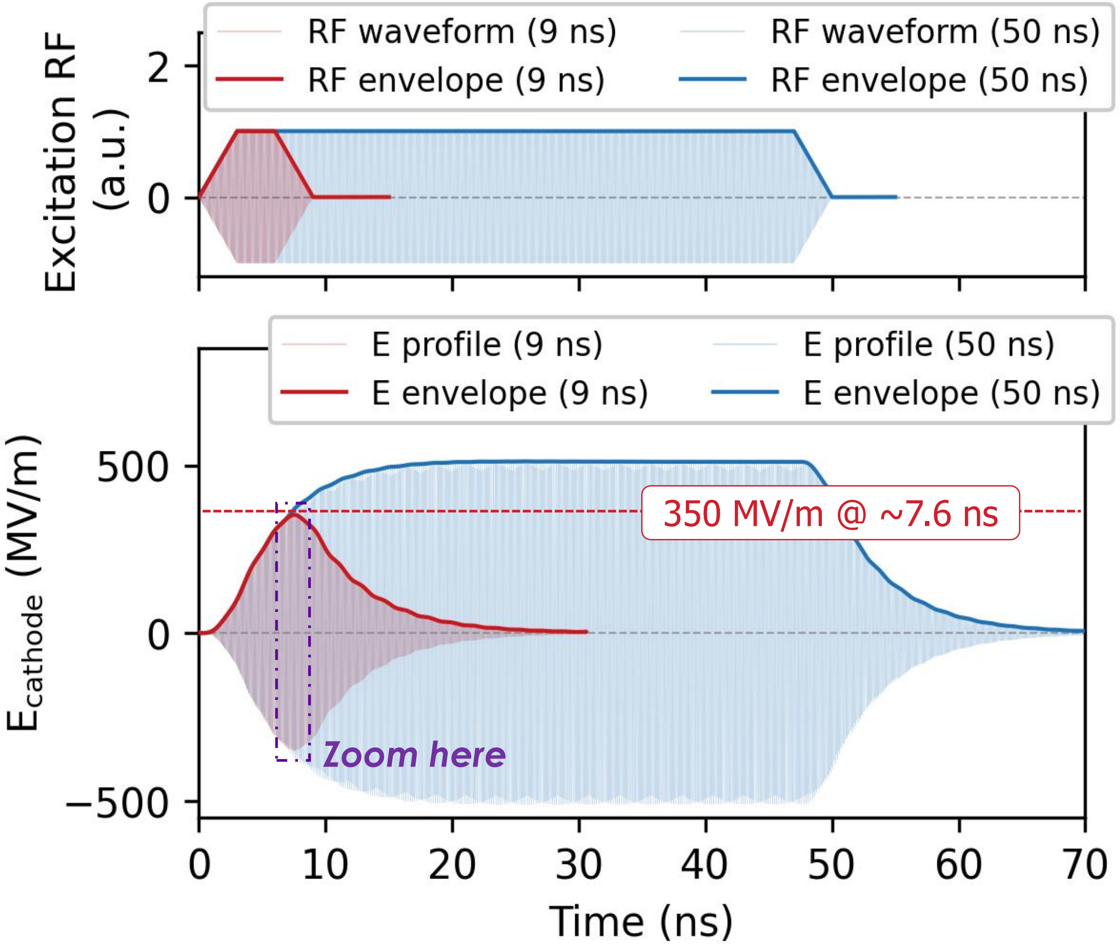
- Understand the RF buildup process during the short pulse filling
- Potential effects on the beam performance



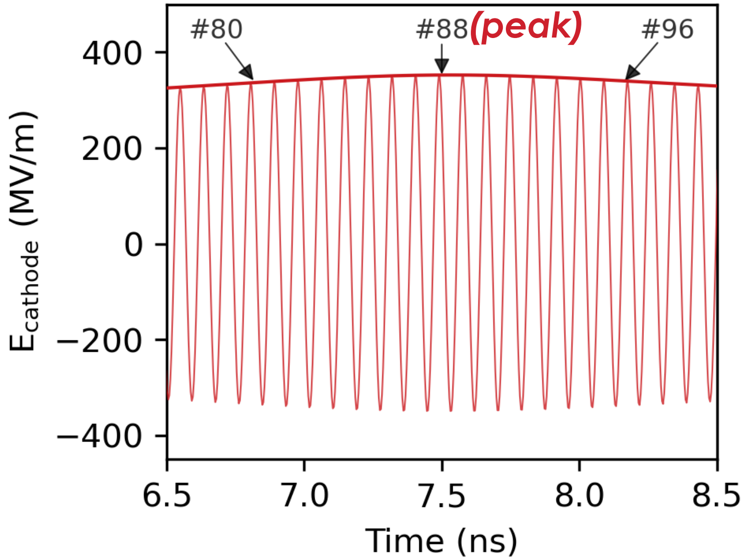
RF BUILD UP PROCESS

E-field on cathode: 9 ns vs. *“long”* 50 ns





Zoom-in
around the mostly filled region



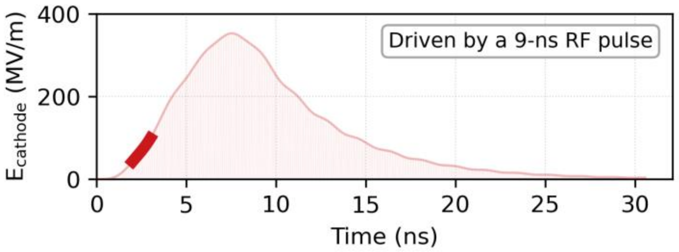
- If driven by 9 ns pulse, Xgun is under-filled and staying in the transient state during the full RF duration.
- E-field on cathode is changing cycle by cycle.
- Broad high-gradient operational window.

G. Chen, et al., *arXiv*: arXiv:2503.09575. doi: 10.48550/arXiv.2503.09575.

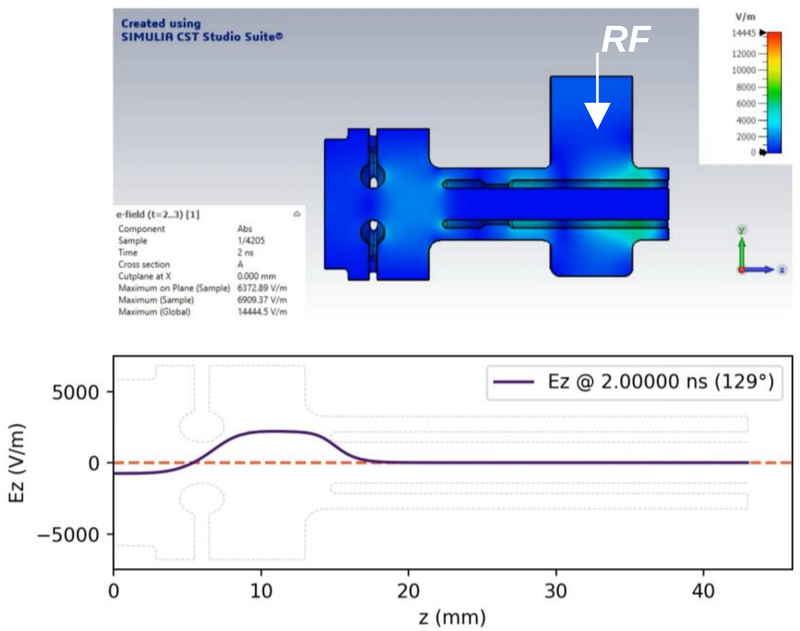
RF BUILD UP PROCESS

Spatial evolution of E-field: 9 ns vs. *"long"* 50 ns

E_cathode (2 ns to 3 ns)

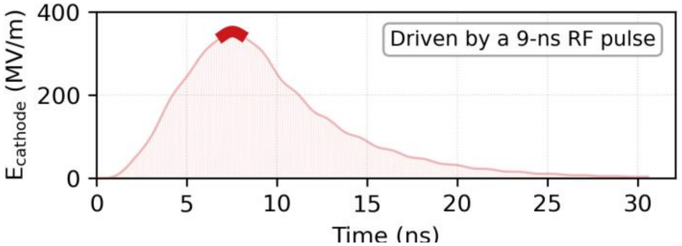


On-axis Ez (2 ns to 3 ns)

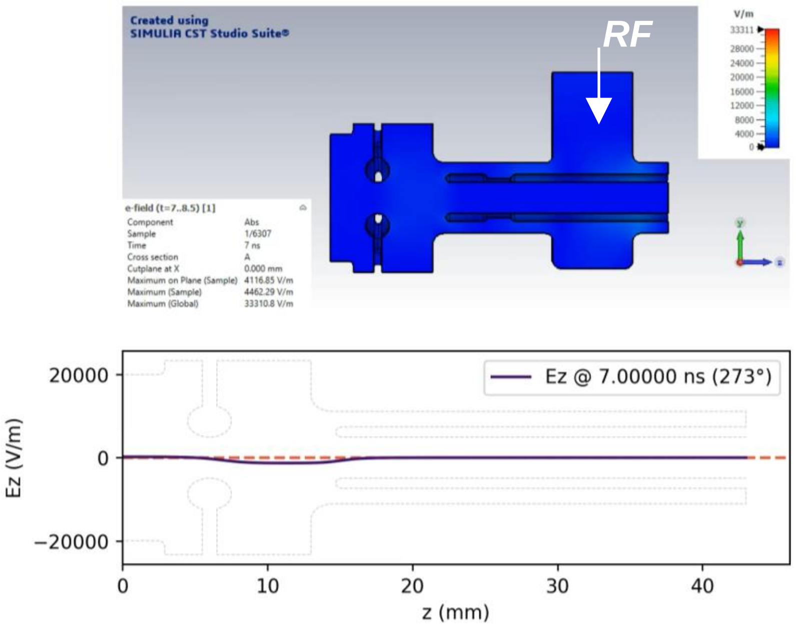


e-field (t=2..3) [1]
Component Abs
Sample 1/4205
Time 2 ns
Cross section A
Cutplane at X 0.000 mm
Maximum on Plane (Sample) 6372.89 V/m
Maximum (Sample) 6909.37 V/m
Maximum (Global) 14444.5 V/m

E_cathode (7 ns to 8 ns)

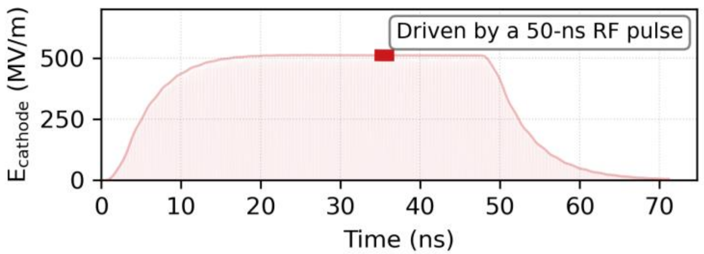


On-axis Ez (7 ns to 8 ns)

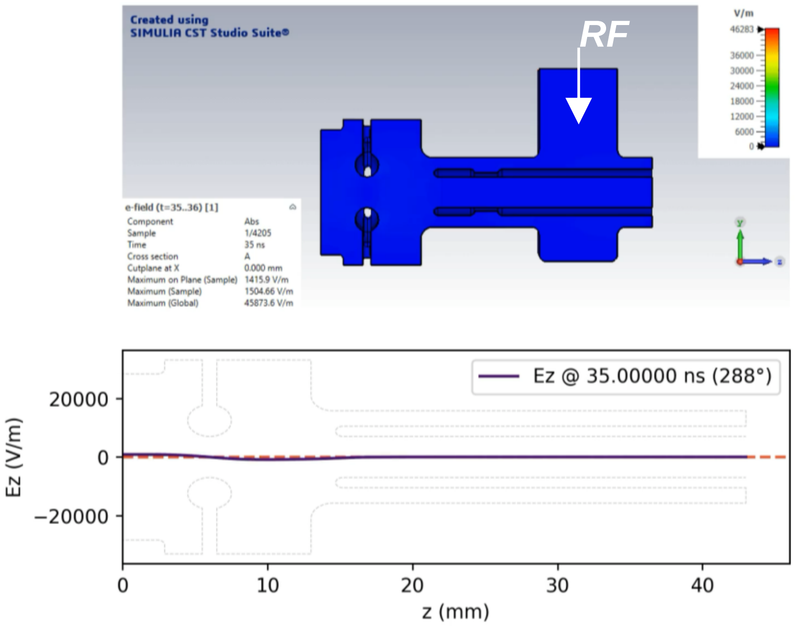


e-field (t=7..8.5) [1]
Component Abs
Sample 1/6307
Time 7 ns
Cross section A
Cutplane at X 0.000 mm
Maximum on Plane (Sample) 4116.85 V/m
Maximum (Sample) 4462.29 V/m
Maximum (Global) 33310.8 V/m

E_cathode (35 ns to 36 ns)



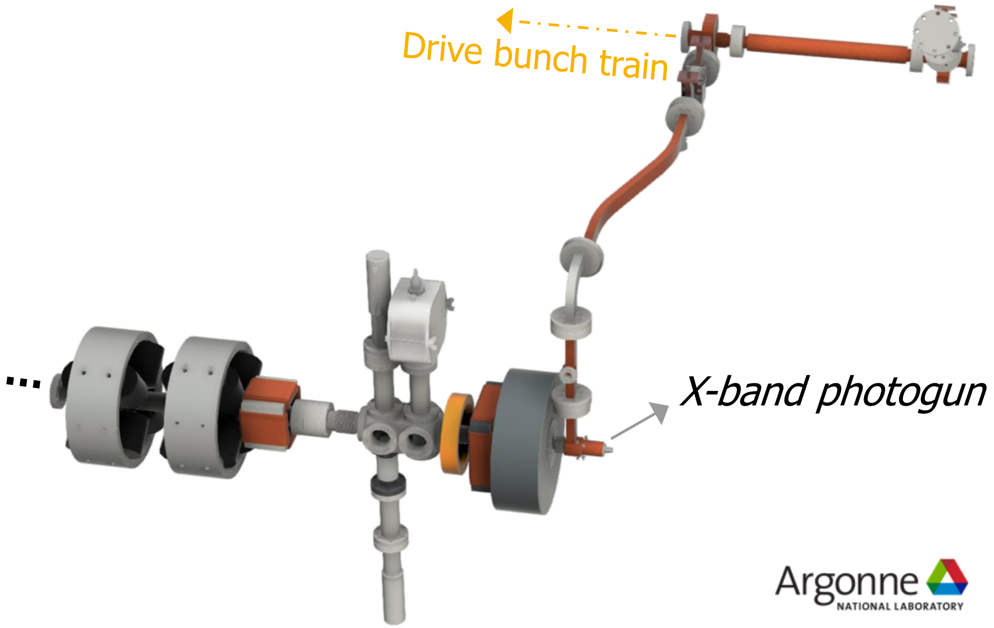
On-axis Ez (35 ns to 36 ns)



e-field (t=35..36) [1]
Component Abs
Sample 1/4205
Time 35 ns
Cross section A
Cutplane at X 0.000 mm
Maximum on Plane (Sample) 1415.9 V/m
Maximum (Sample) 1504.66 V/m
Maximum (Global) 45873.6 V/m

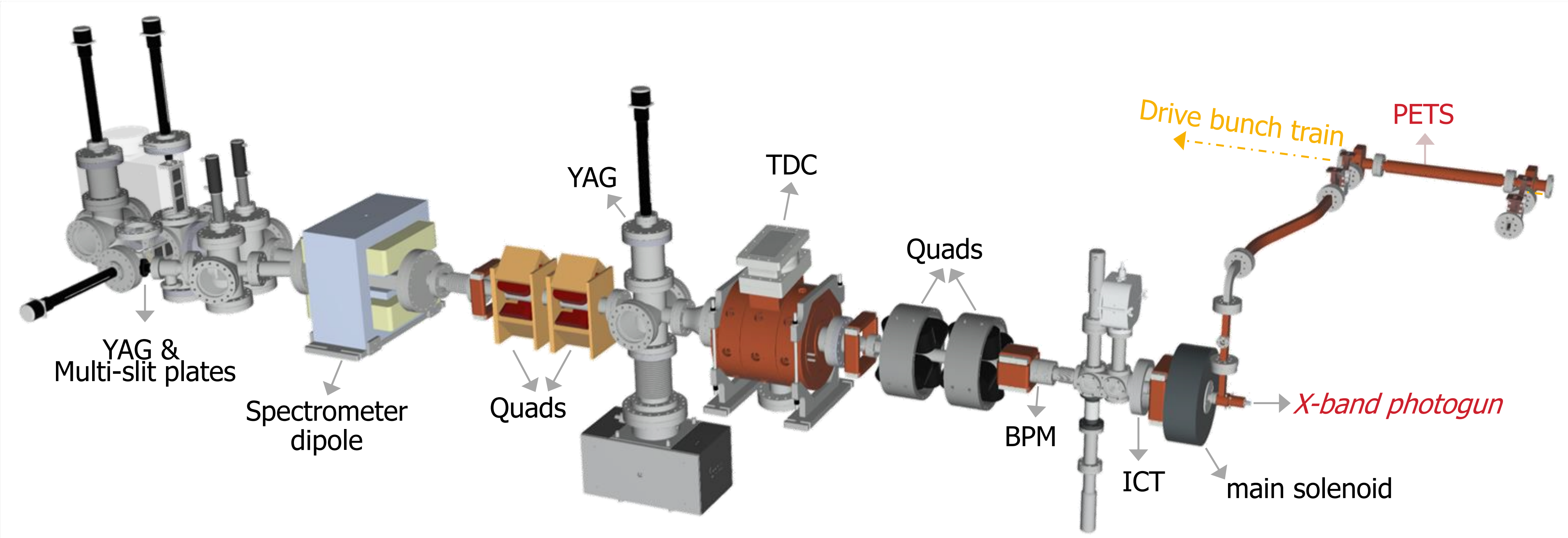
RECENT WORK:
LONGITUDINAL PHASE SPACE (LPS)

- Measured bunch lengths
- Projected emittance, slice emittance



RECENT BEAM TEST

Beamline in 2025

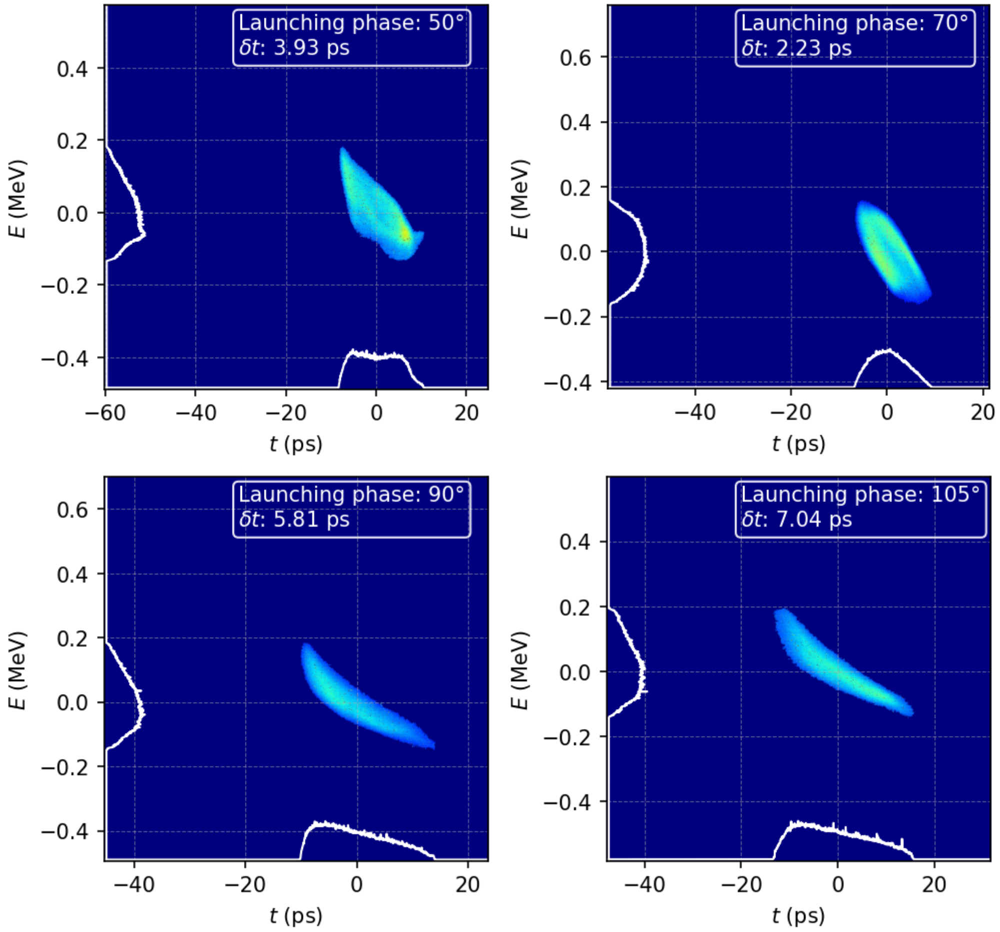


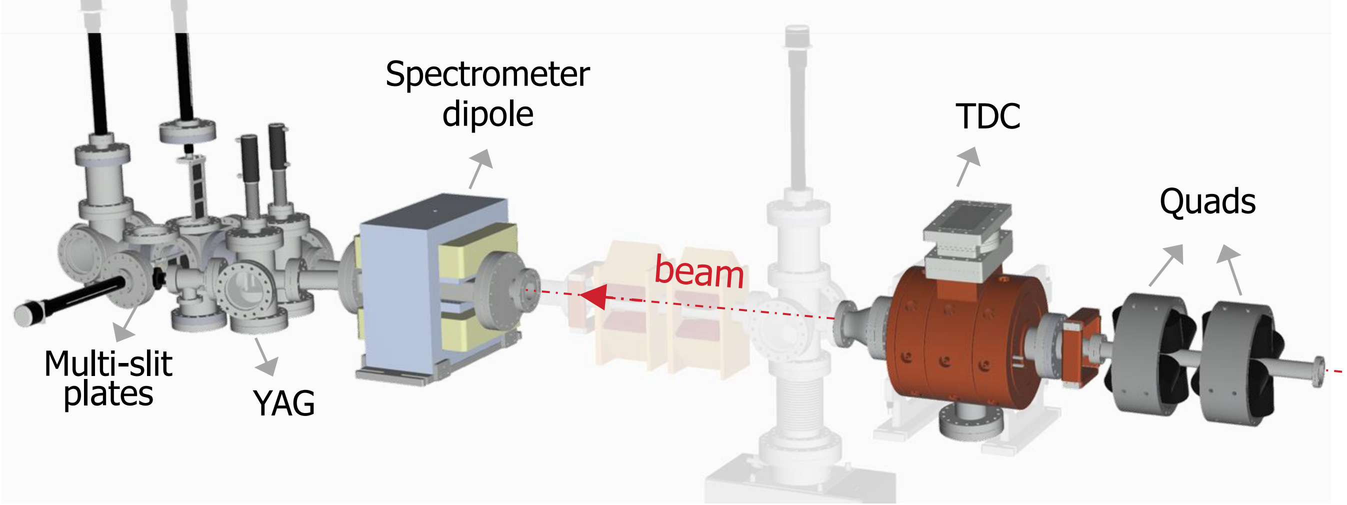
- Given the current resources, a deflecting cavity (TDC) was installed into the beamline. We try to characterize the longitudinal phase space (LPS):
  - Bunch lengths at different injection phases
  - Slice emittance measurement

LPS PHASE SPACE MEASUREMENT

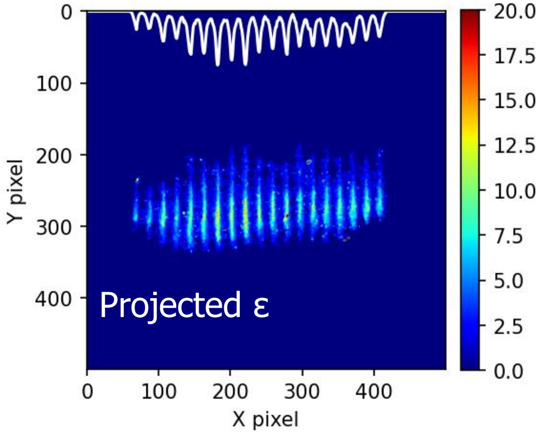
Preliminary σ_z and ε

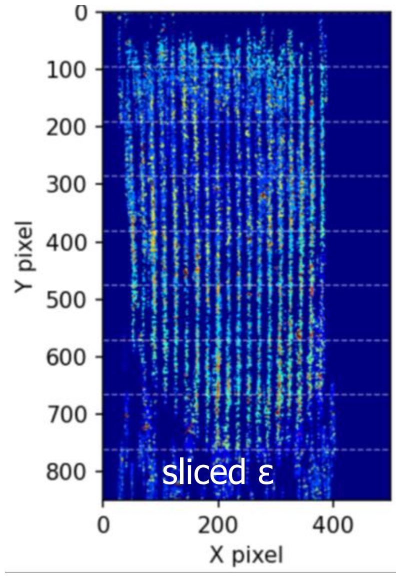
LPS and σ_z @ different phases:





Projected ε and slice ε:





Analysis ongoing…

FUTURE WORK: NEW LINAC DEVELOPMENT

- Introduction to the design concept
- Preliminary design

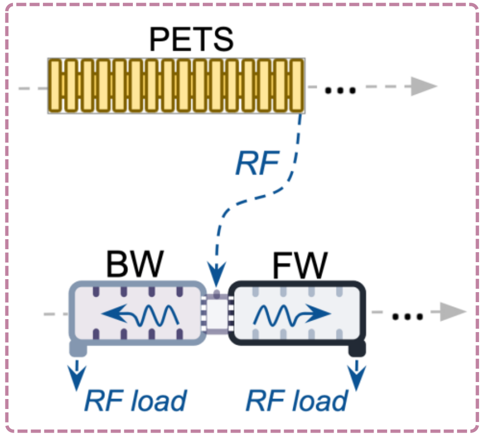
SHORT-PULSE POWERED LINAC

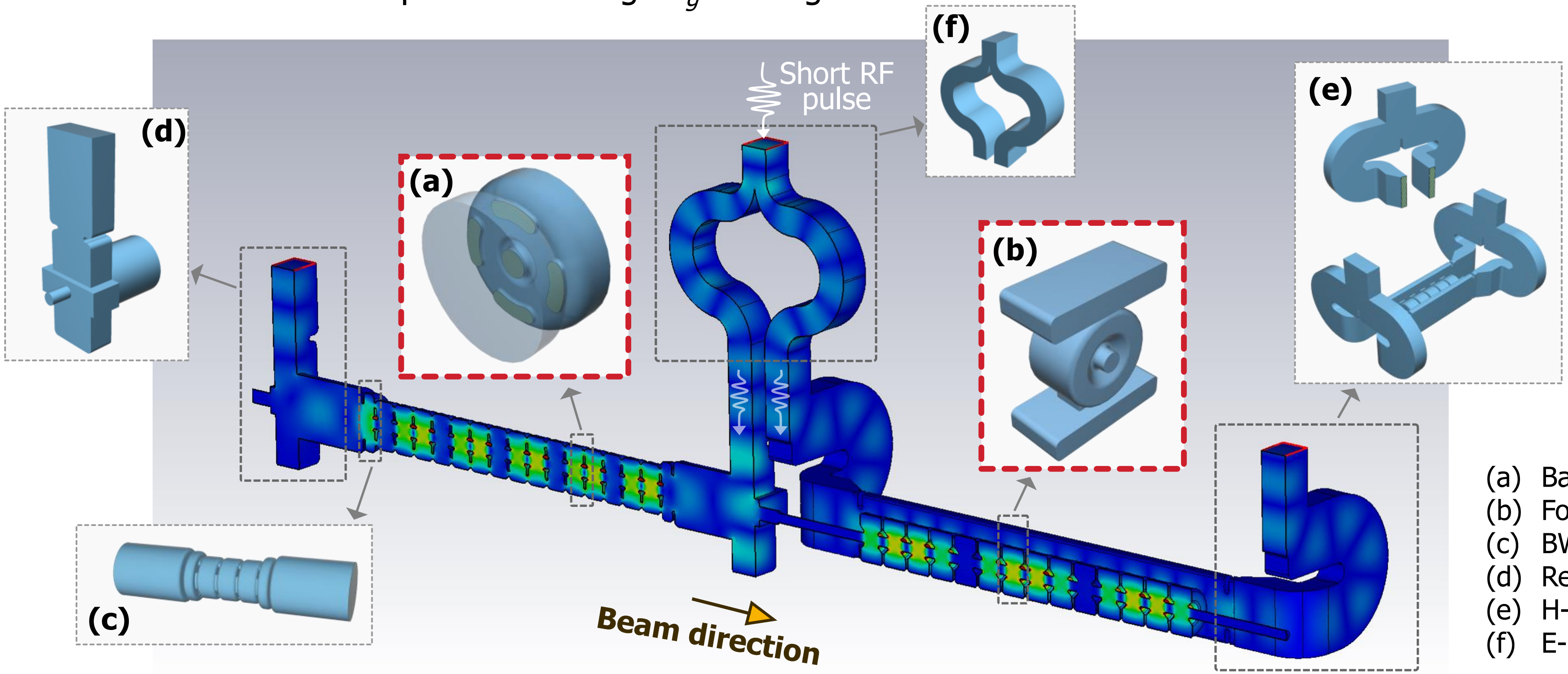
On-going effort

Design concept:

- To maximize the energy gain, a compact LINAC with longer accelerating length is needed.
- We proposed a two-half BW-FW structure to extend the structure length, with each section optimized for high v_g and high r.

Concept





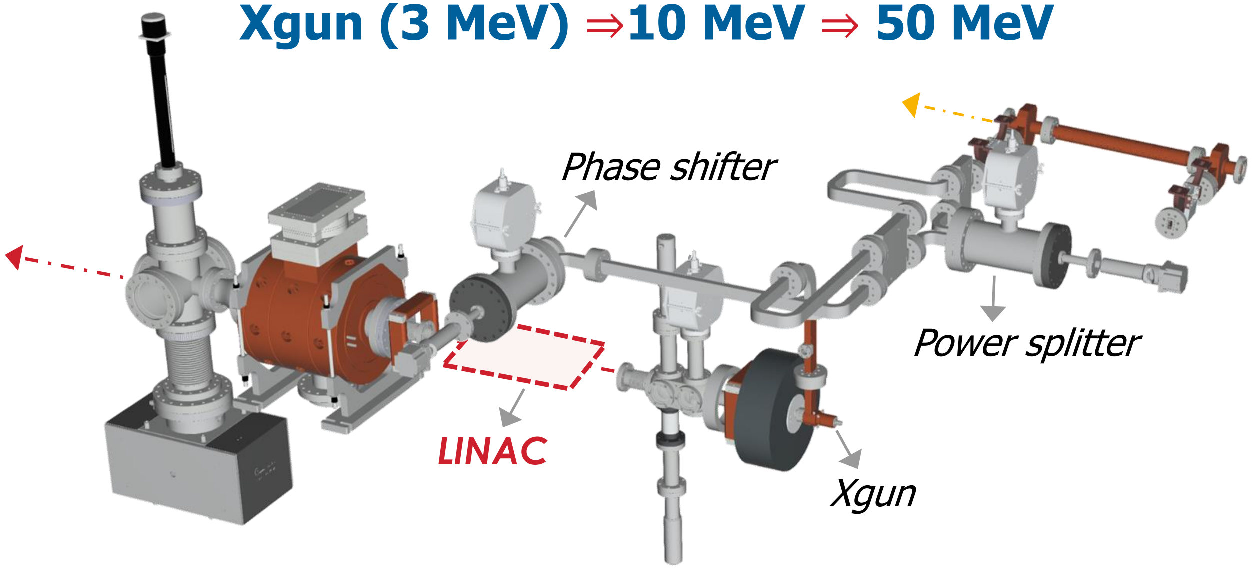
(a) Backward wave (BW) single cell
(b) Forward wave (FW) single cell
(c) BW matching cell
(d) Rectangular-to-circular adapter
(e) H-plane power divider & FW matching slots
(f) E-plane power divider

[1] G. Chen, et al., Proceedings of IPAC’26, 2026. doi: 10.18429/JACoW-IPAC2026-TUV3301.

FUTURE WORK AND CONCLUSION

Xgun upgrade

Xgun (3 MeV) ⇒10 MeV ⇒ 50 MeV



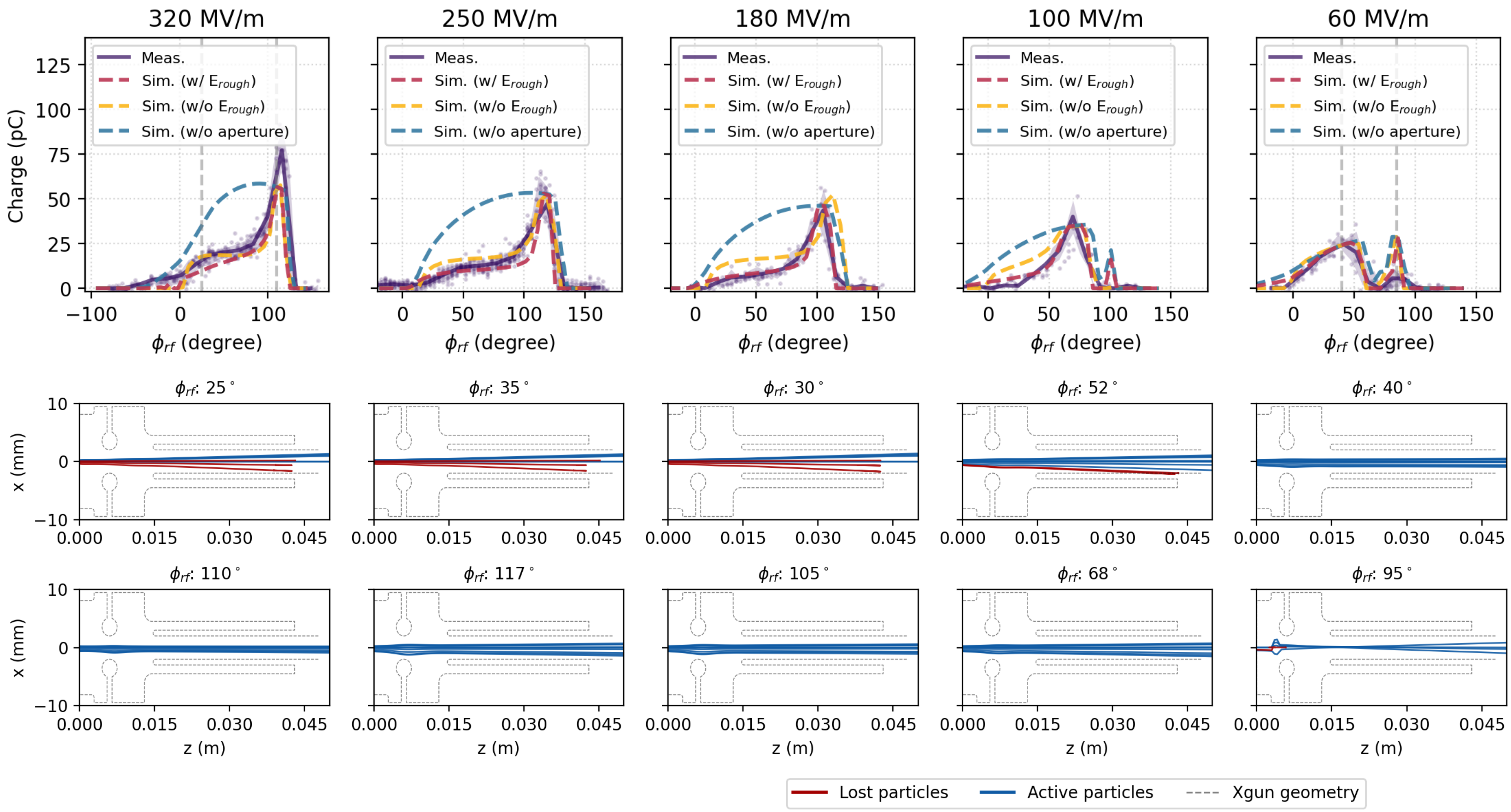
- **New photogun and solenoid** design.
- **Near term (3 MeV⇒10 MeV):** Add an in-house conventional linac to reach 10 MeV, and quantify beam performance. With one PETS powering both the X-gun and linac.
- **Long term (⇒50 MeV):** Add a second "PETS-linac" module for further energy scaling.

- Short-pulse operation is promising, with gradients >350 MV/m demonstrated in the X-gun.
- Short-pulse operation also introduce challenges, such as rapid filling time, and potential transient effects in underfilled structures.
- The ultimate goal is *100 pC with 100 nm* emittance.

Thank you!

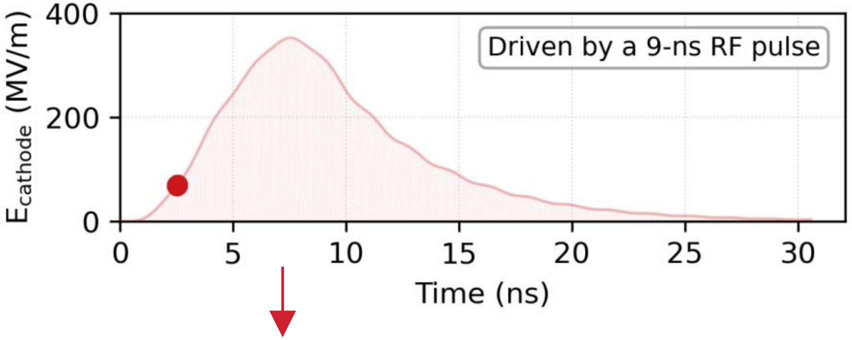
BACKUP

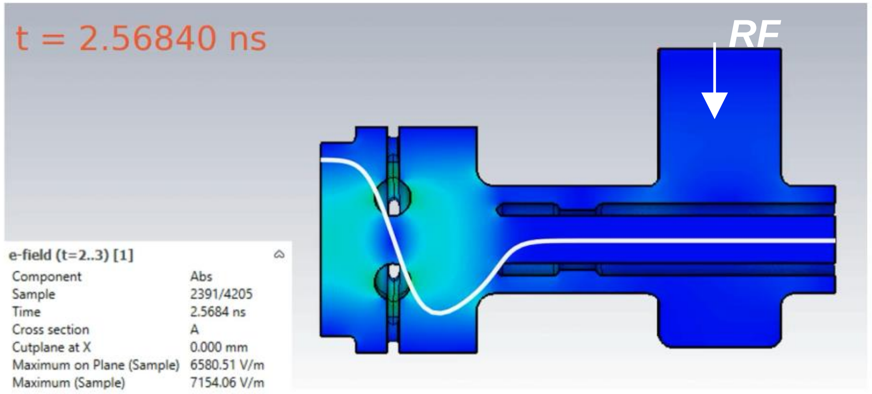
PHASE SCAN + BEAM TRAJECTORY



CLOSER LOOK ON Ez (on-axis)

Early filled stage (~2.5 ns)

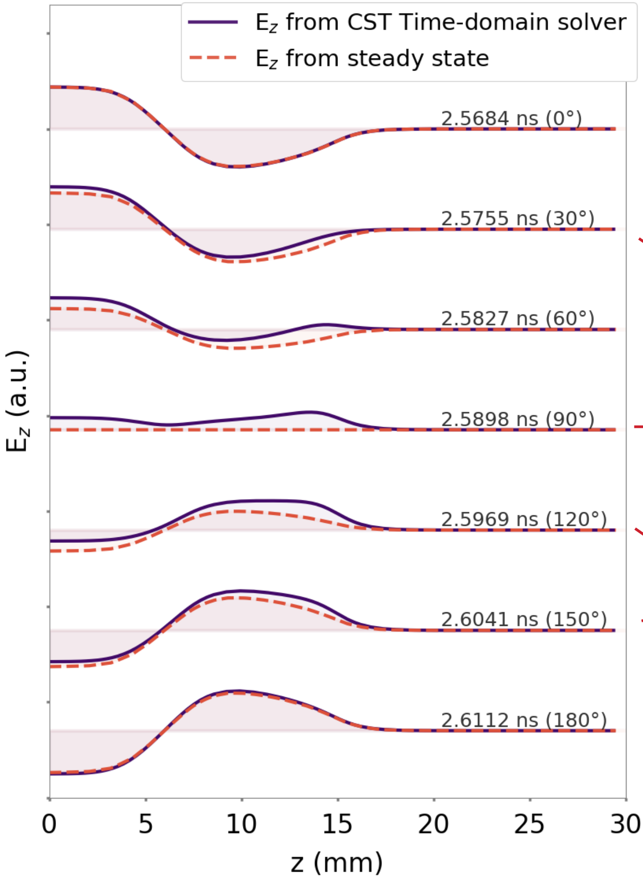




e-field (t=2..3) [1]

Component	Abs
Sample	2391/4205
Time	2.5684 ns
Cross section	A
Cutplane at X	0.000 mm
Maximum on Plane (Sample)	6580.51 V/m
Maximum (Sample)	7154.06 V/m

Selected snapshots



Standing wave (SW) cavity:

$$E = E_0 \cdot cos(\omega t + \phi)$$

Clear Deviation from the pure SW Cavity.

"0-mode" like distribution

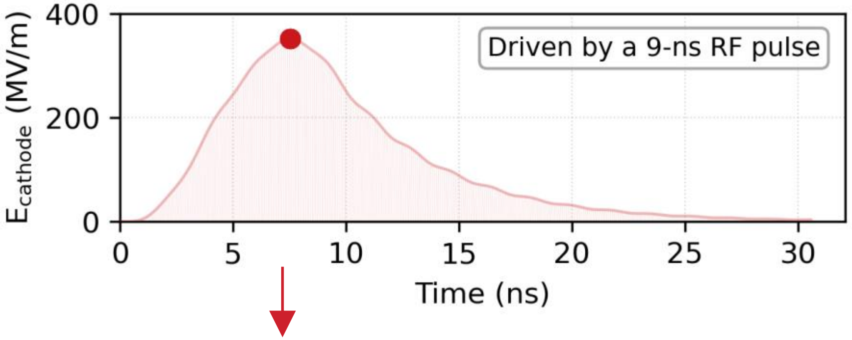
Clear Deviation from the pure SW Cavity.

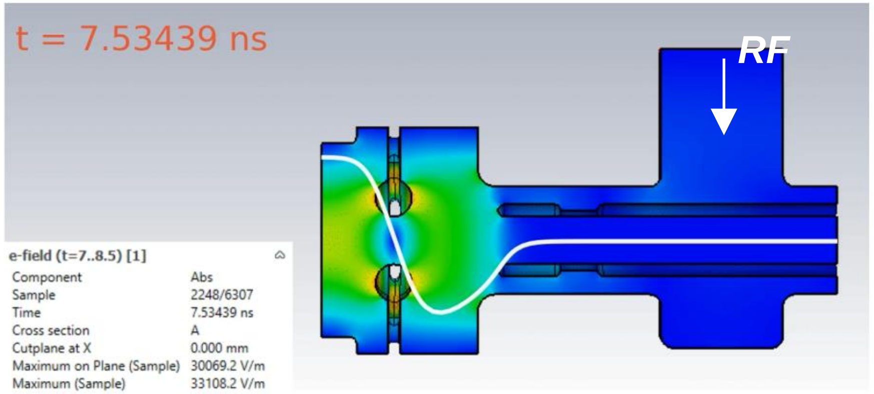
- Before reaching to steady states, different coupling between sections causes non-uniform RF power flow, making some sections respond to the RF faster while others lag, showing a delayed or "0-mode"-like field patterns.

G. Chen, et al., *arXiv*: arXiv:2503.09575. doi: 10.48550/arXiv.2503.09575.

CLOSER LOOK ON Ez (on-axis)

Mostly filled stage (~7.5 ns)



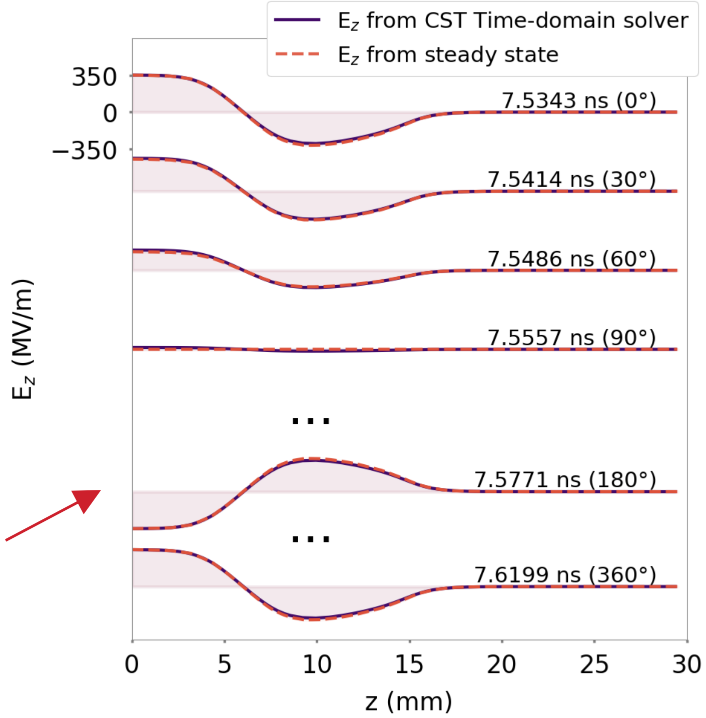


t = 7.53439 ns

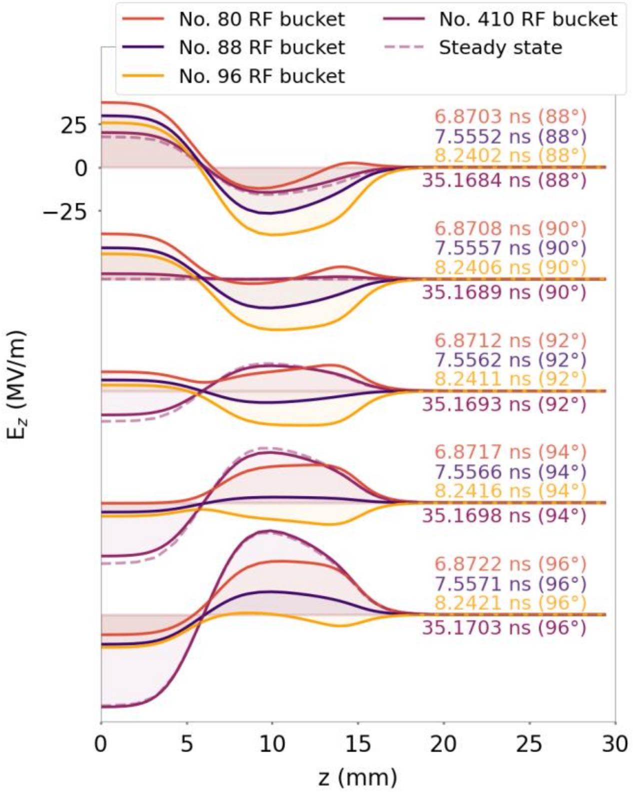
e-field (t=7..8.5) [1]

Component	Abs
Sample	2248/6307
Time	7.53439 ns
Cross section	A
Cutplane at X	0.000 mm
Maximum on Plane (Sample)	30069.2 V/m
Maximum (Sample)	33108.2 V/m

Selected snapshots from #88 RF bucket



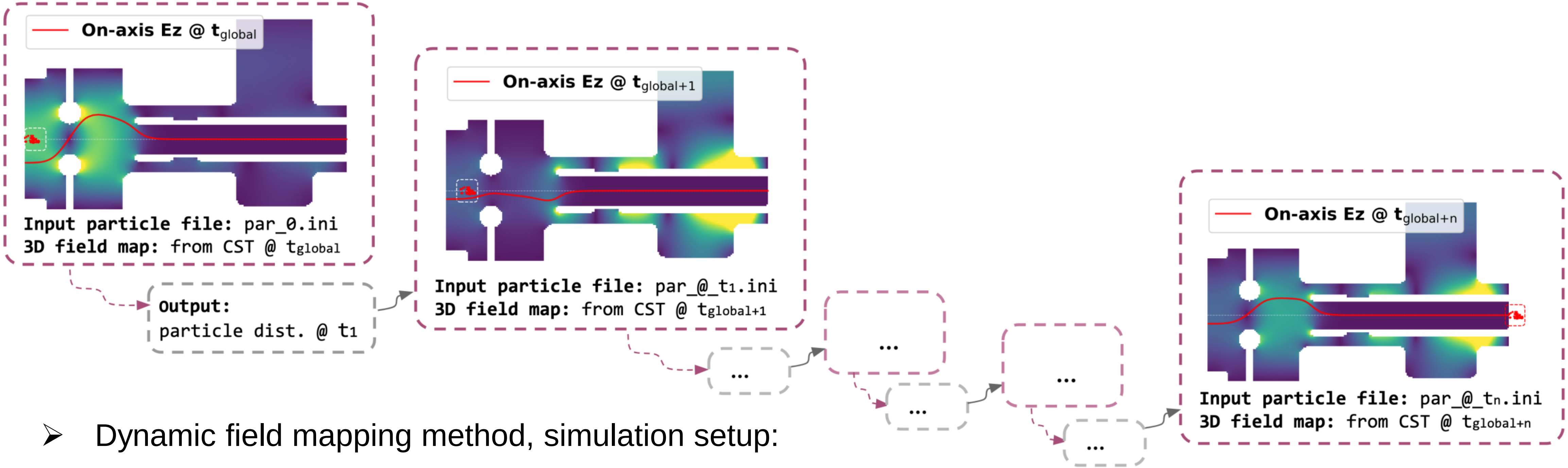
Ez phases 88°–96° RF buckets #80, #88, #96, & steady-state



- When the Xgun is under-filled in the transient states, the EM field distribution varies cycle-by-cycle. This transient behavior is different from pure SW cavity.
- *This **transient effect** needs to be considered in beam simulations.*

BEAM SIMULATION WORKFLOW

Include the transient field map


On-axis Ez @ t_{global}

Input particle file: par_0.ini
3D field map: from CST @ t_{global}

Output:
particle dist. @ t_1

On-axis Ez @ $t_{global+1}$

Input particle file: par_@_t_1.ini
3D field map: from CST @ $t_{global+1}$

…

…

…

…

…

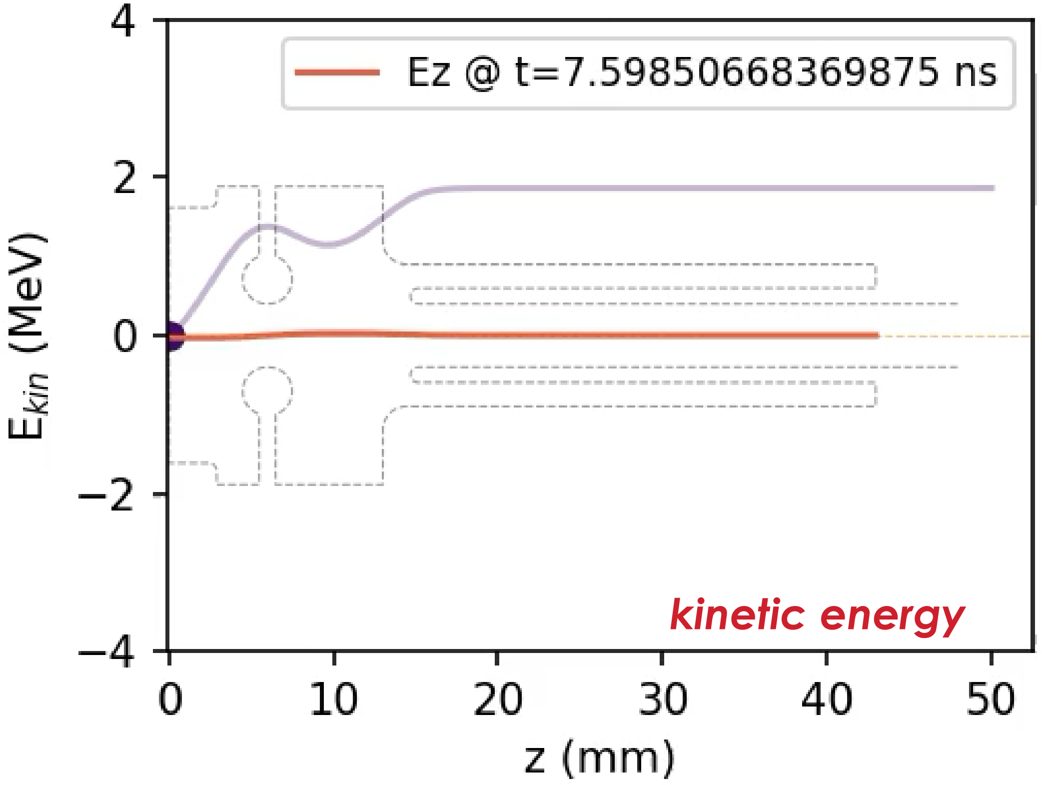
On-axis Ez @ $t_{global+n}$

Input particle file: par_@_t_n.ini
3D field map: from CST @ $t_{global+n}$

- Dynamic field mapping method, simulation setup:
  - Update field map every ~0.2 ps (1° at X-band).
  - Use 3D field map
  - Zero thermal emittance; no solenoid; ignore space charge
- In the following work, we focus on characterizing beam properties (kinetic energy, transverse emittance, and bunch length) with the influence only from transient RF field.

AN EXAMPLE OF BEAM TRACKING

With dynamic field mapping



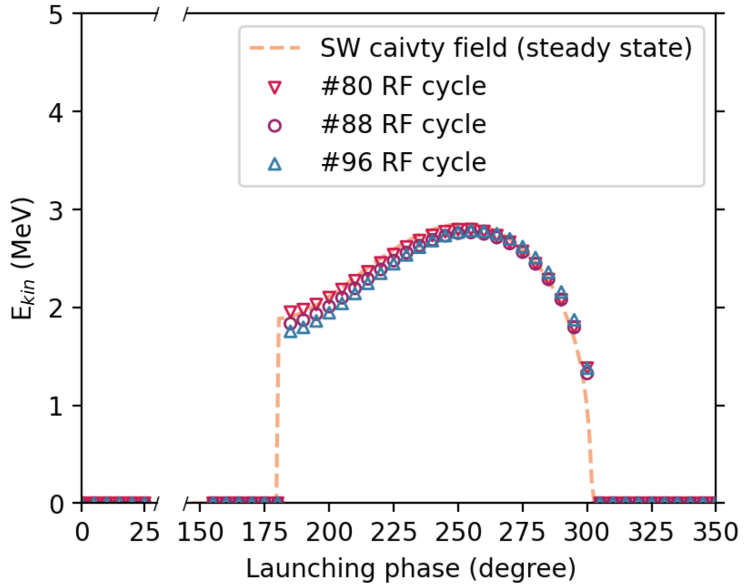
- ➢ Launch the beam from #88 bucket at the launching phase of 185°.
- ➢ Update field map every 0.2 ps. On-axis Ez (red curve) plotted for reference.
- ➢ Track the bunch to the gun exit, and record the results (i.e. kinetic energy in this example).

- ➢ Then repeat this process for launching phase 0° to 360° → *next slide*

BEAM PERFORMANCE SUMMARY

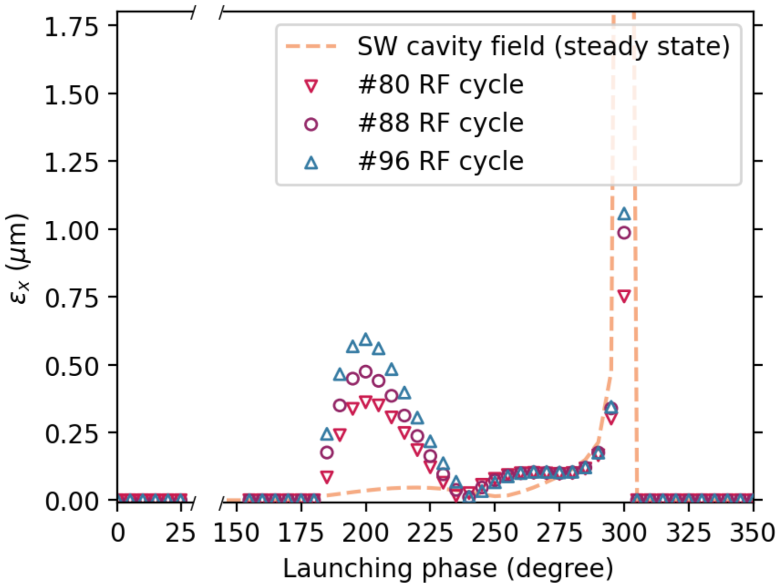
Kinetic energy, emittance, bunch length

kinetic energy vs. launching phase



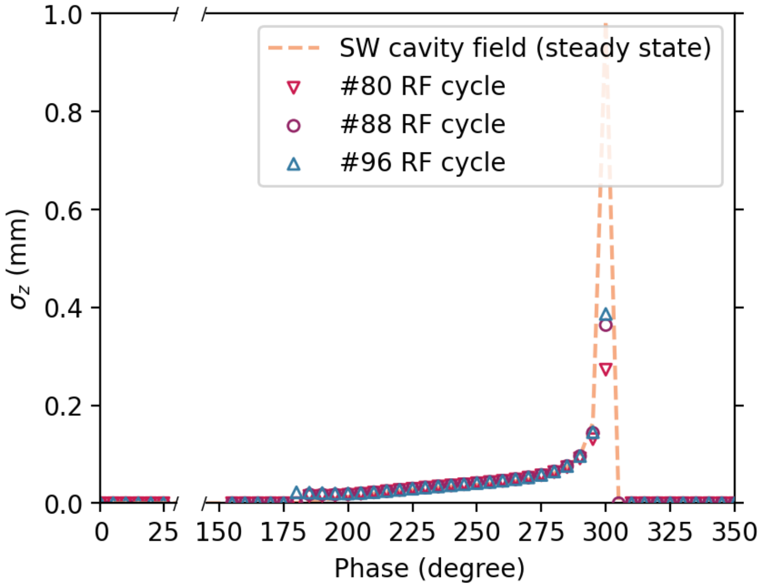
- ➢ Small effect.

emittance vs. launching phase



- ➢ The value of the min emittance is similar as SW cavity (nearly no change). However, the phase is different.

bunch length vs. launching phase

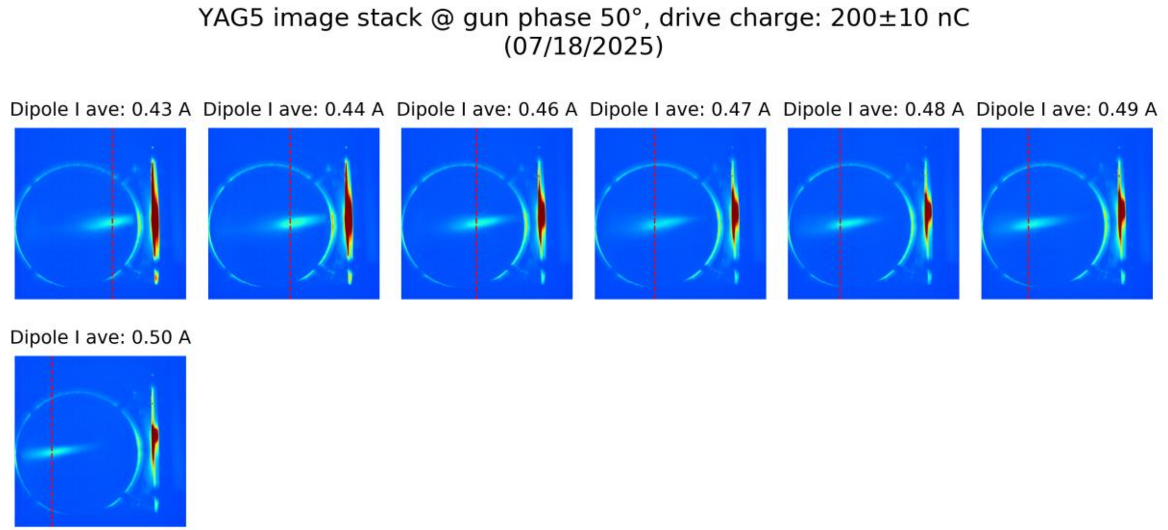


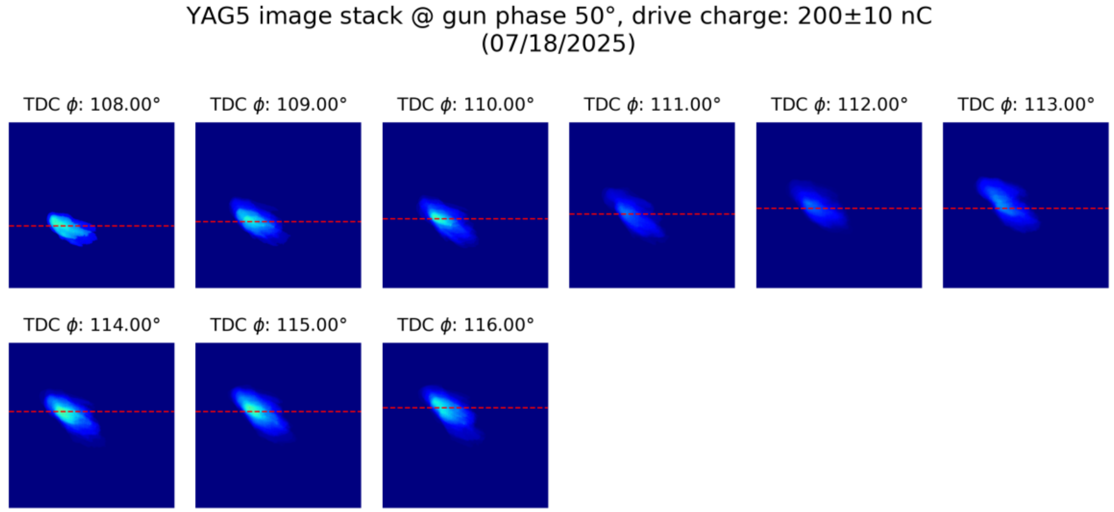
- ➢ Very small effect.

G. Chen, et al., *arXiv*: arXiv:2503.09575. doi: 10.48550/arXiv.2503.09575.

LPS DATA calibration

E and time calibration


YAG5 image stack @ gun phase 50°, drive charge: 200±10 nC
(07/18/2025)


YAG5 image stack @ gun phase 50°, drive charge: 200±10 nC
(07/18/2025)