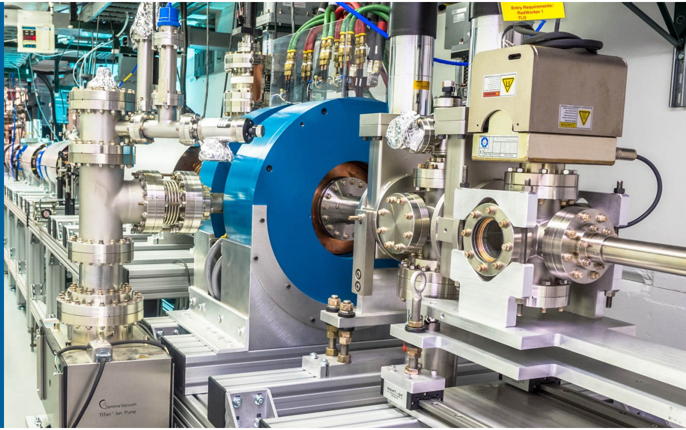
Argonne NATIONAL LABORATORY

PROGRESS REPORT ON AN X-BAND ULTRA-HIGH GRADIENT PHOTOINJECTOR



GONGXIAOHUI CHEN
on behalf of joint efforts from AWA, Euclid Techlabs and NIU

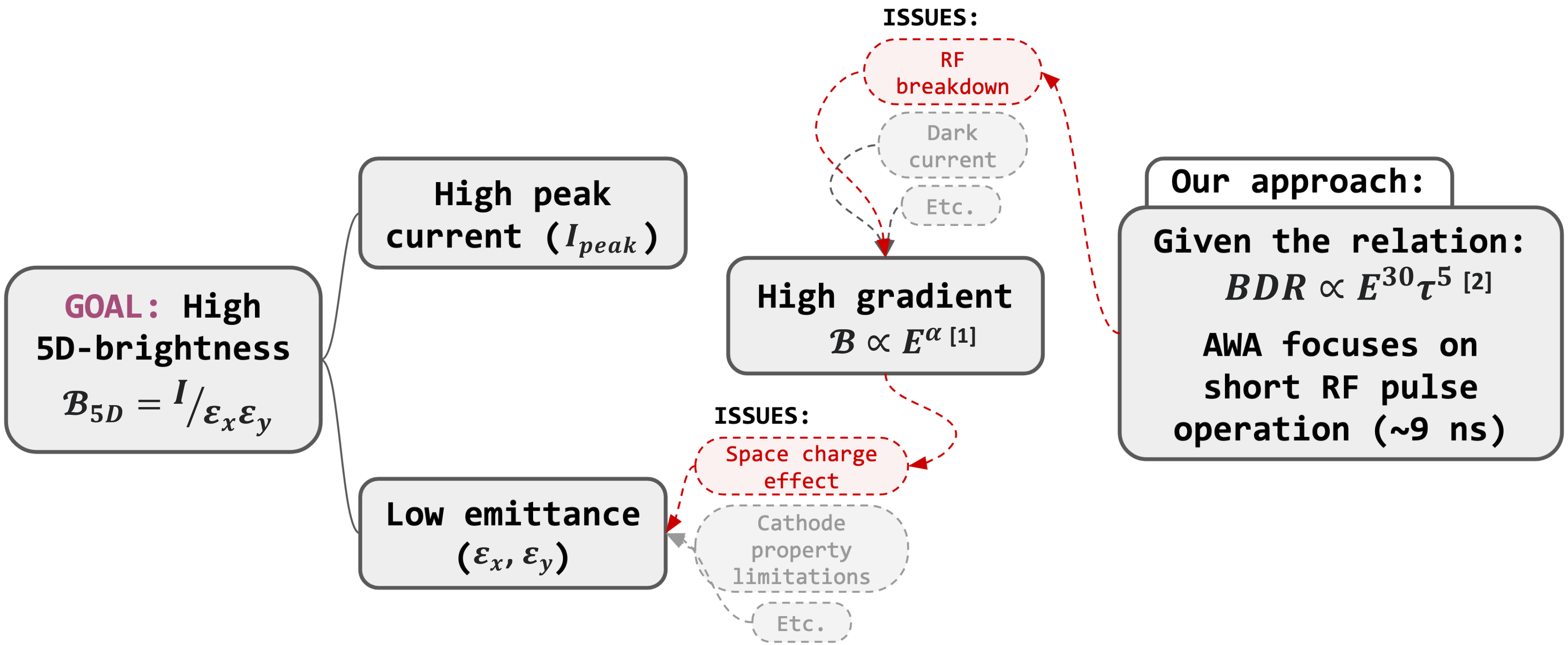
07/22/2024

OUTLINE

- Motivation
- Introduction:
  - AWA main beamline
  - X-band photogun (Xgun) beamline
  - Basic rf properties on Xgun structure
- Some highlights on Xgun test history
- Most recent work:
  - Xgun Schottky studies at different gradients
  - Simulation benchmarking
- Future work

OUR APPROACH TO HIGH BRIGHTNESS

Motivation



[1] I. V. Bazarov *et. al.*, Phys. Rev. Lett. 102, 104801 (2009).

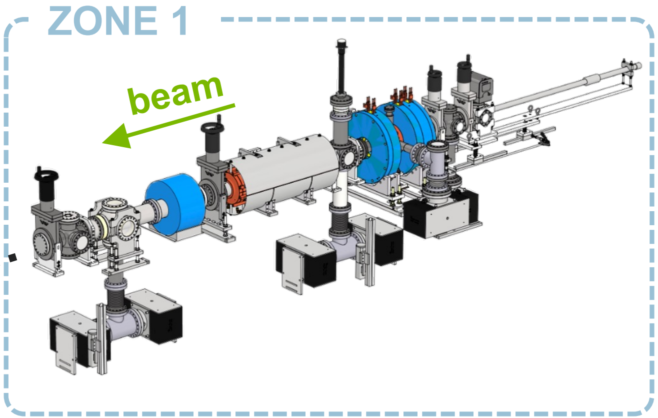
[2] A. Grudiev *et. al.*, Phys. Rev. ST-AB, 12, 102001 (2009).

INTRODUCTION TO AWA BEAMLINES

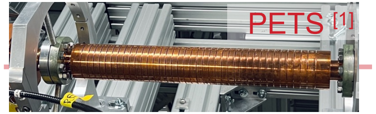
- Main drive beamline (deliver high charge bunch train)
- Xgun beamline (powered by “drive beamline”)

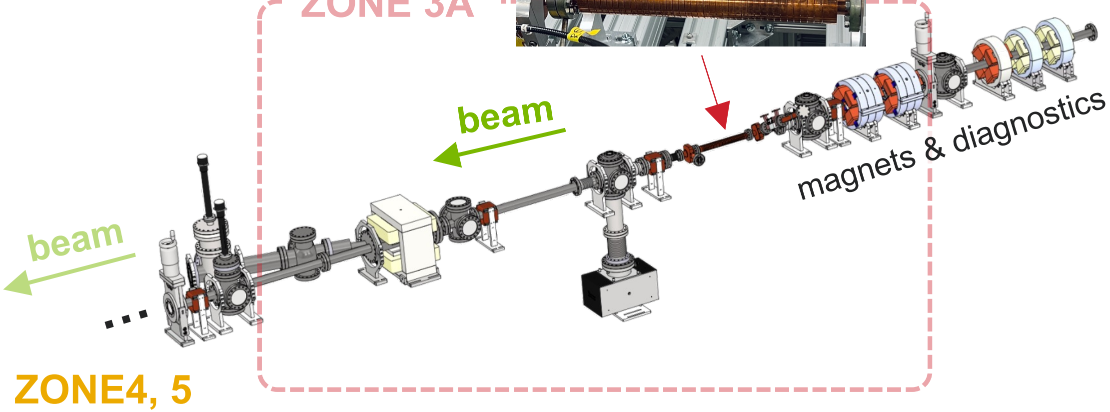
INTRODUCTION TO AWA DRIVE BEAMLINE

- Fully re-configurable
- Currently have a metallic Power Extraction and Transfer Structure (PETS) installed
- PETS: for high power short-pulse rf generation



- L-band drive gun
- Cs_2Te cathode
- High charge bunch train (up to 600 nC)
- Final beam energy: ~65 MeV

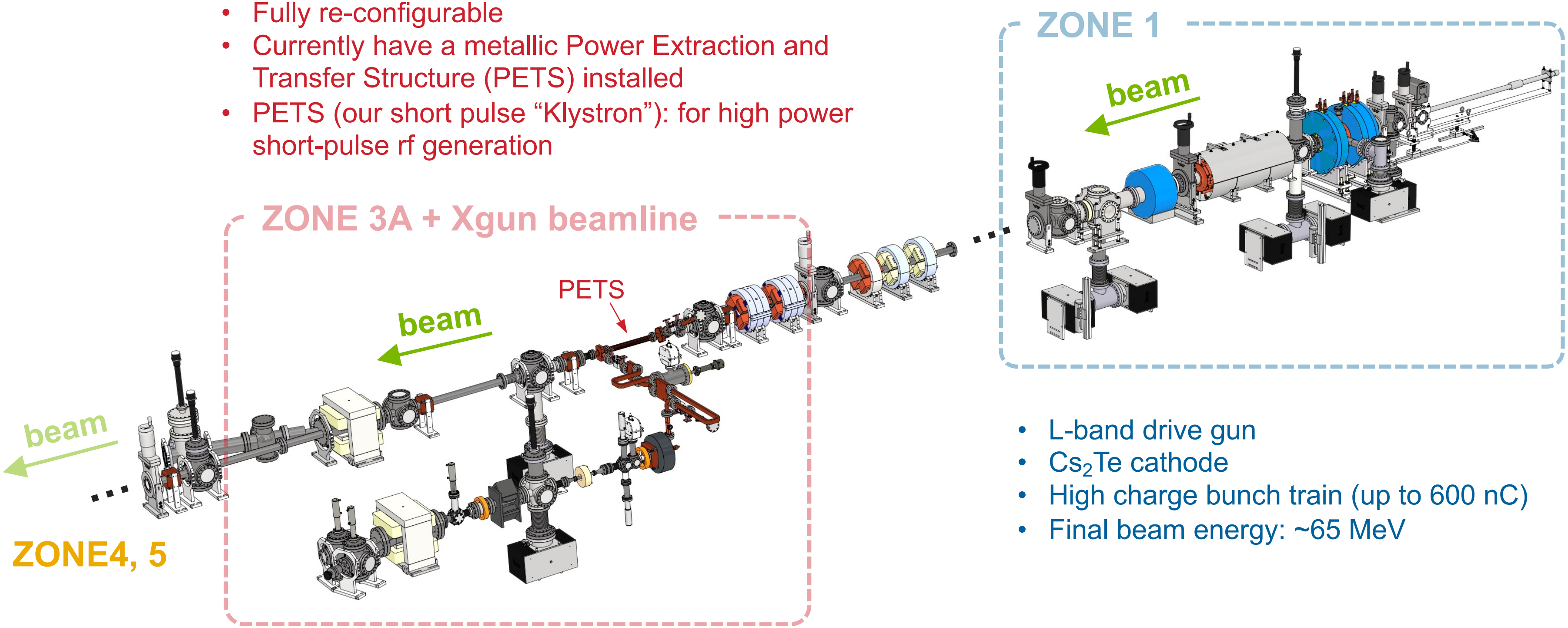




[1] J. Shao *et. al.*, doi:10.18429/ JACoW- IPAC2019- MOPRB069 (2019)

INTRODUCTION TO AWA DRIVE BEAMLINE

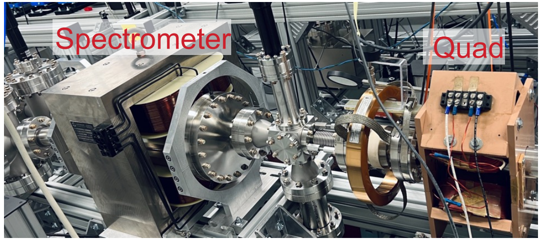
- Fully re-configurable
- Currently have a metallic Power Extraction and Transfer Structure (PETS) installed
- PETS (our short pulse “Klystron”): for high power short-pulse rf generation

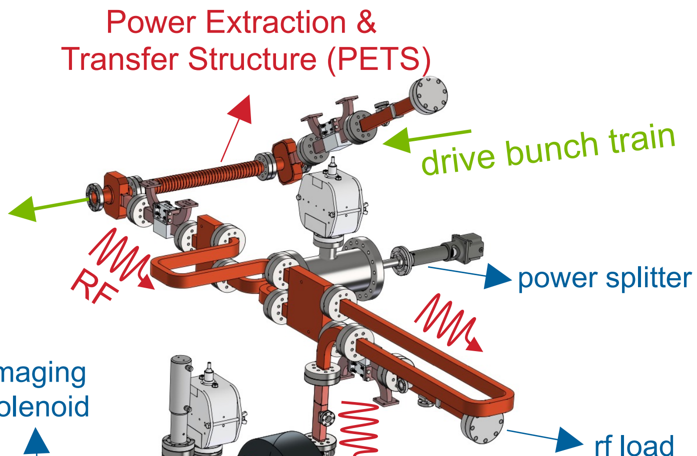


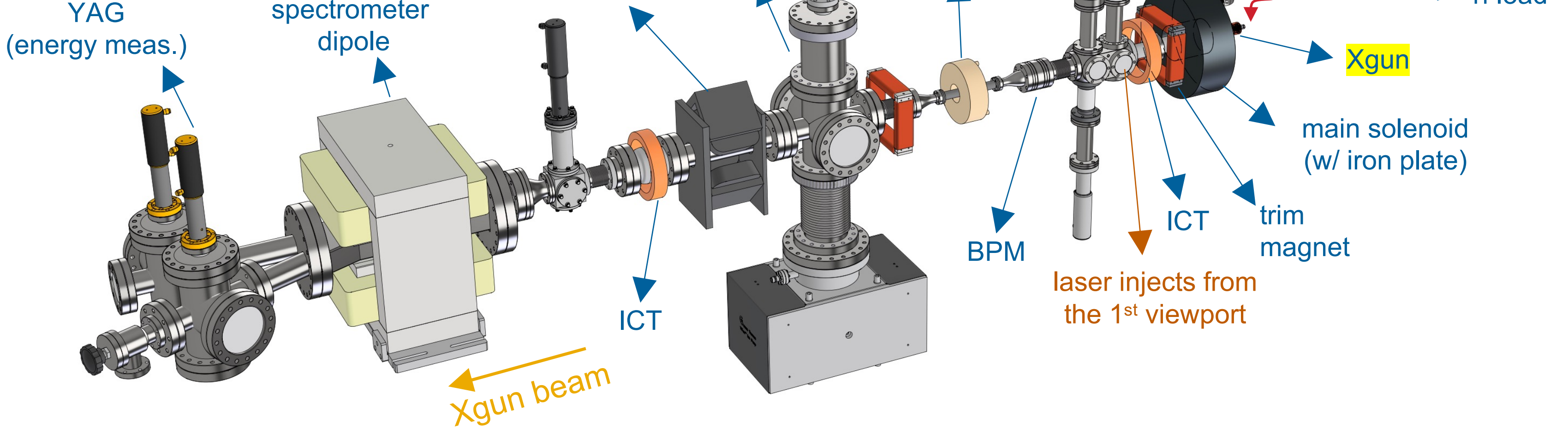
- L-band drive gun
- Cs_2Te cathode
- High charge bunch train (up to 600 nC)
- Final beam energy: ~65 MeV

XGUN BEAMLINE

2023 config. (will upgrade this summer)



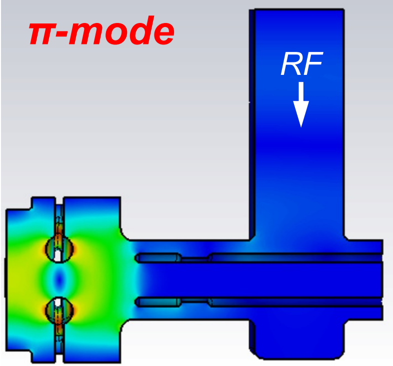


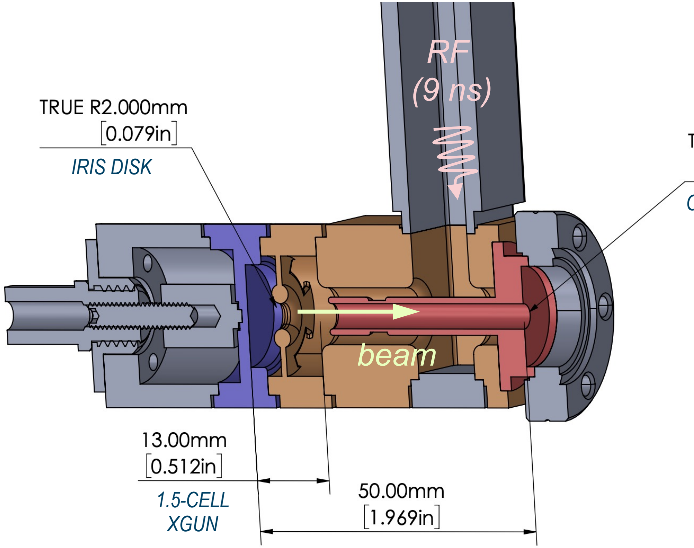


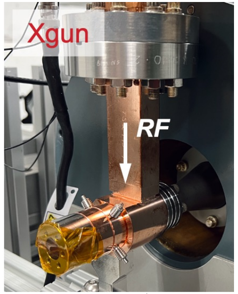
SHORT PULSE XGUN DESIGN

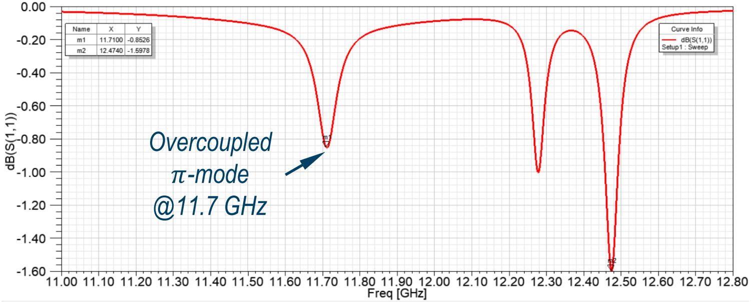
Brief introduction

- X-band 1.5-cell rf gun (Xgun)
- Operate on π-mode @11.7 GHz
- Short rf pulse (9 ns) operation
- Strongly over-coupled
  - Short fill-time
  - Q_load≈180
- Cathode is the copper backwall of the Xgun cavity









XGUN TEST HISTORY

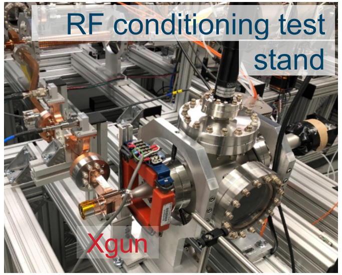
Selected highlights since 2020

[1] W.H.Tan *et. al.,* Phys. Rev. Accel. Beams 25, 083402, August 2022 (2022)

pre-2020

Initial Xgun RF conditioning [1]

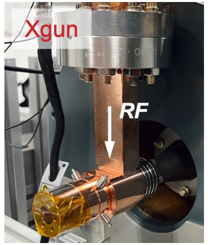
- Achieved 350 MV/m within 70k pulses.
- A dark current loading region observed.
- No observable dark current after conditioning.



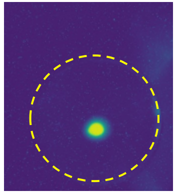
2021

1st beam test [1]

- High gradient (**388 MV/m**) verified through beam energy measurement.
- Beam energy characterized (~3% fluctuation).
- Low breakdown rate confirmed (>500,000 shots, BDR<10^{-5}).



Beam on YAG1



2022

2nd beam test & re-conditioning

- X-band power splitter and phase shifter conditioned.
- A LINAC added to the Xgun beamline. Beam energy characterized.
- Performed another rf conditioning, very few BD noticed. Good robustness.

2023

3rd beam test (most recent)

- Study the fundamentals of photoemission (Copper cathode):
  - Schottky studies at different gradients.
  - QE measurements at different gradients.

Next section

FUNDAMENTAL PHOTOEMISSION STUDIES

- Schottky scans @ different gradients (60 MV/m to 320 MV/m)
- Simulation benchmarking
- Exploring the potential for other emission mechanisms
- Exploring the potential for multipacting

SCHOTTKY STUDIES

Simulation benchmarking of exp. data

Simulation setup

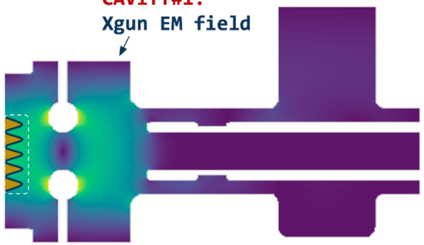
In ASTRA, bunch charge is evaluated as follows,

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

where,

S_1, S_2: Schottky strength coefficients

E: field on the cathode



Possible field (E) contributions acting on the cathode:

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

Both included in ASTRA ($E_0 \cdot sin(\varphi_{rf}) + E_{sc}$)

Modeled separately using a sinusoidal surface [1-2] ($E_{roughness}$)

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.

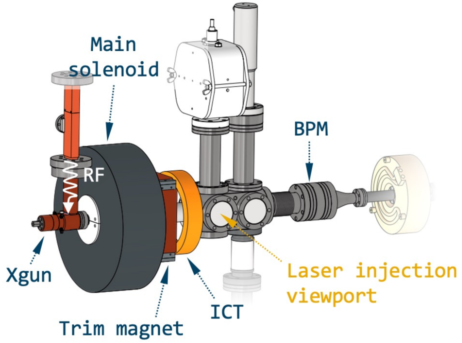


Table 1: List of the simulation parameters in ASTRA

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)

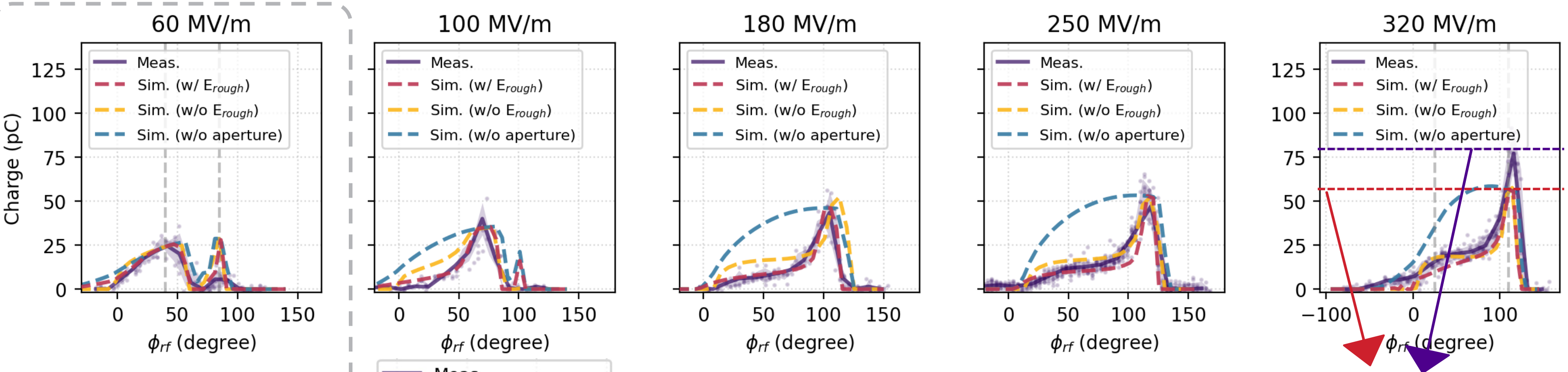
[1] D. J. Bradley, et al., J. Phys. D: Appl. Phys., Vol. 10, (1977).
[2] G. S. Gevorkyan, et al., Phys. Rev. Accel. Beams 21, 093401 (2018).

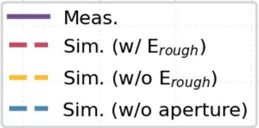
SCHOTTKY STUDIES

Simulation benchmarking of exp. data @ 60, 100, 180, 250, 320 MV/m

In ASTRA, bunch charge is evaluated as follows,

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



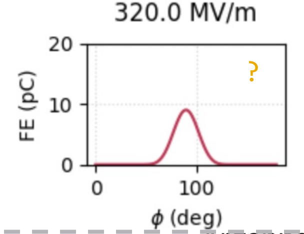


Ref data for simulation param (S_1, S_2, Q_0) optimization

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

Modified Folwer-Nordheim:

$$J(E) = a\frac{\beta^2 E^2}{\phi_{eff}}\exp(-b\,\frac{\phi_{eff}^{3/2}}{\beta E})$$

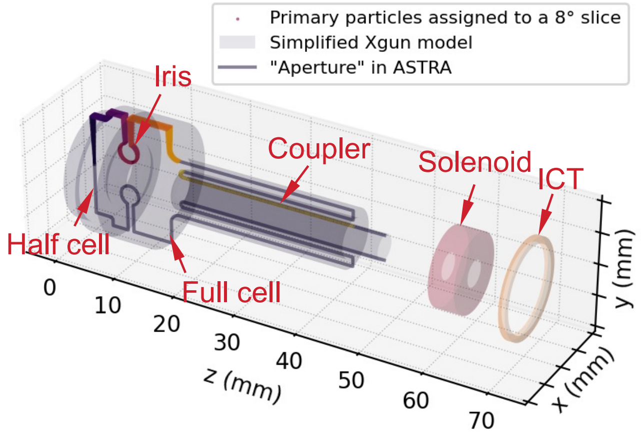


- At all gradients, simulations include the $E_{roughness}$ shows a better agreement with the measurements.
- Revealed a beam clipping issue at the Xgun exit.
- Photo-assisted field emission might happen at high gradient.

MULTIPACTING SIMULATION

@ different gradients

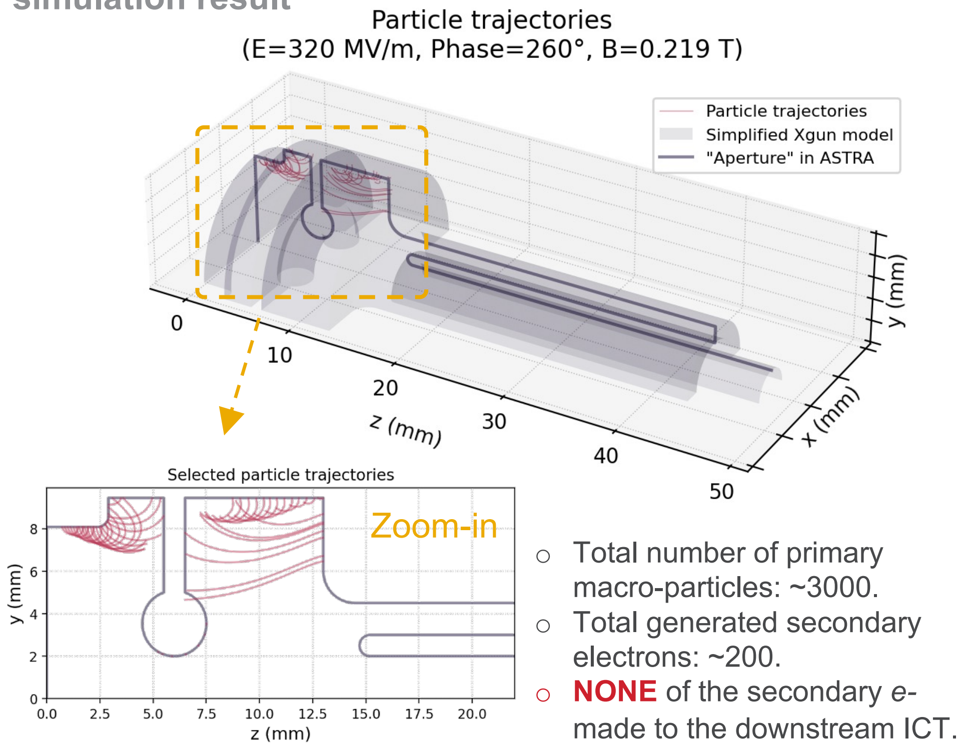
Simulation setup



In the simulation:

- 3D Xgun field map + solenoid field map included.
- Tracking to the downstream ICT.
- Primary particles for MP simulation assigned to an 8 deg slice.
- Cu SEY applied.

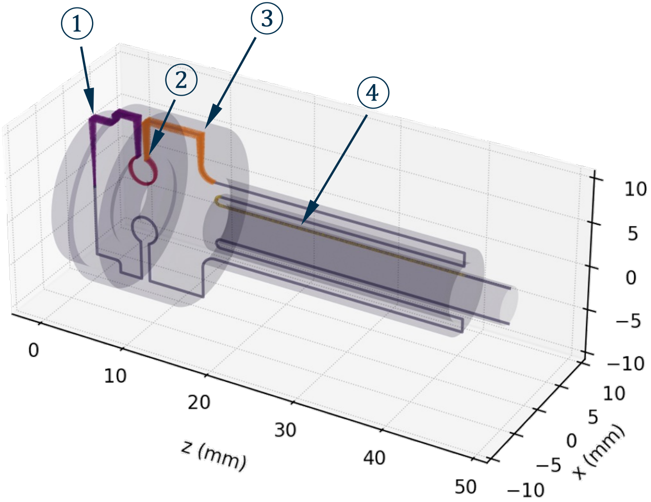
An example of MP simulation result



- Total number of primary macro-particles: ~3000.
- Total generated secondary electrons: ~200.
- **NONE** of the secondary *e*- made to the downstream ICT.

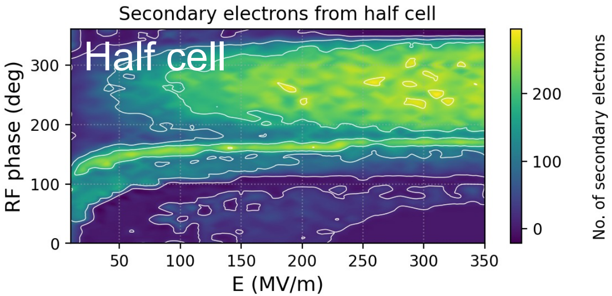
MULTIPACTING SIMULATION

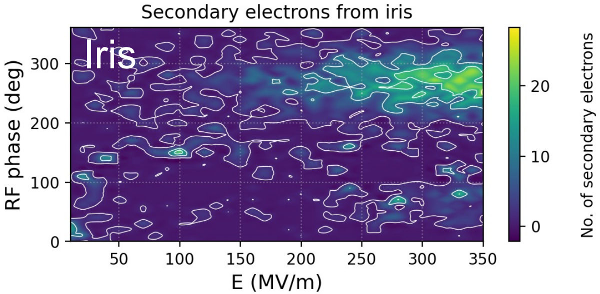
@ different gradients

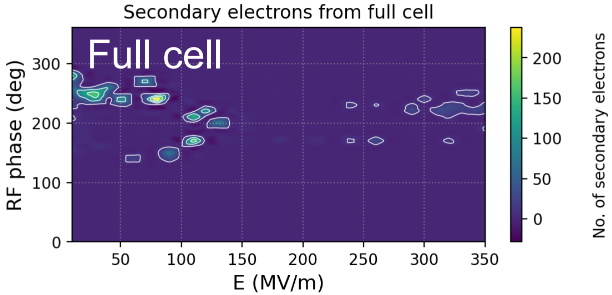


Tracking the MP in different regions separately:

1. Half cell
2. Iris
3. Full cell
4. Coupler (no MP from simulation)







MP scanning param.	
Xgun E	10 to 350 MV/m
Phase	0 to 360 deg
Sol. B*	0.05 to 0.22 T

* Solenoid B for each scan was predicted based on the recorded experimental values

- Get an insight on the MP issue which is sensitive to the **gradient**, **rf phase** and **solenoid strength.**
- Nearly **NO** secondary electrons can reach to the downstream ICT.

FUTURE WORK:

- Slice emittance measurement (summer 2024)
- New Xgun under fabrication

CONCLUSION

- Characterized parameters of Xgun, include:
  - High gradient ~400 MV/m
  - Beam energy 2.7 MeV
  - Good robustness. No noticeable BDs after fully conditioning.
- Fundamental cathode studies have been done:
  - Preliminary phase scans at different gradients have been performed.
  - Simulation benchmarking of experimental data.
  - Get an insights on the FE and MP issues through simulations.
- Future work:
  - New beam test in summer 2024
  - New designs of the Xgun have been proposed in parallel

BIG THANKS TO OUR TEAM!

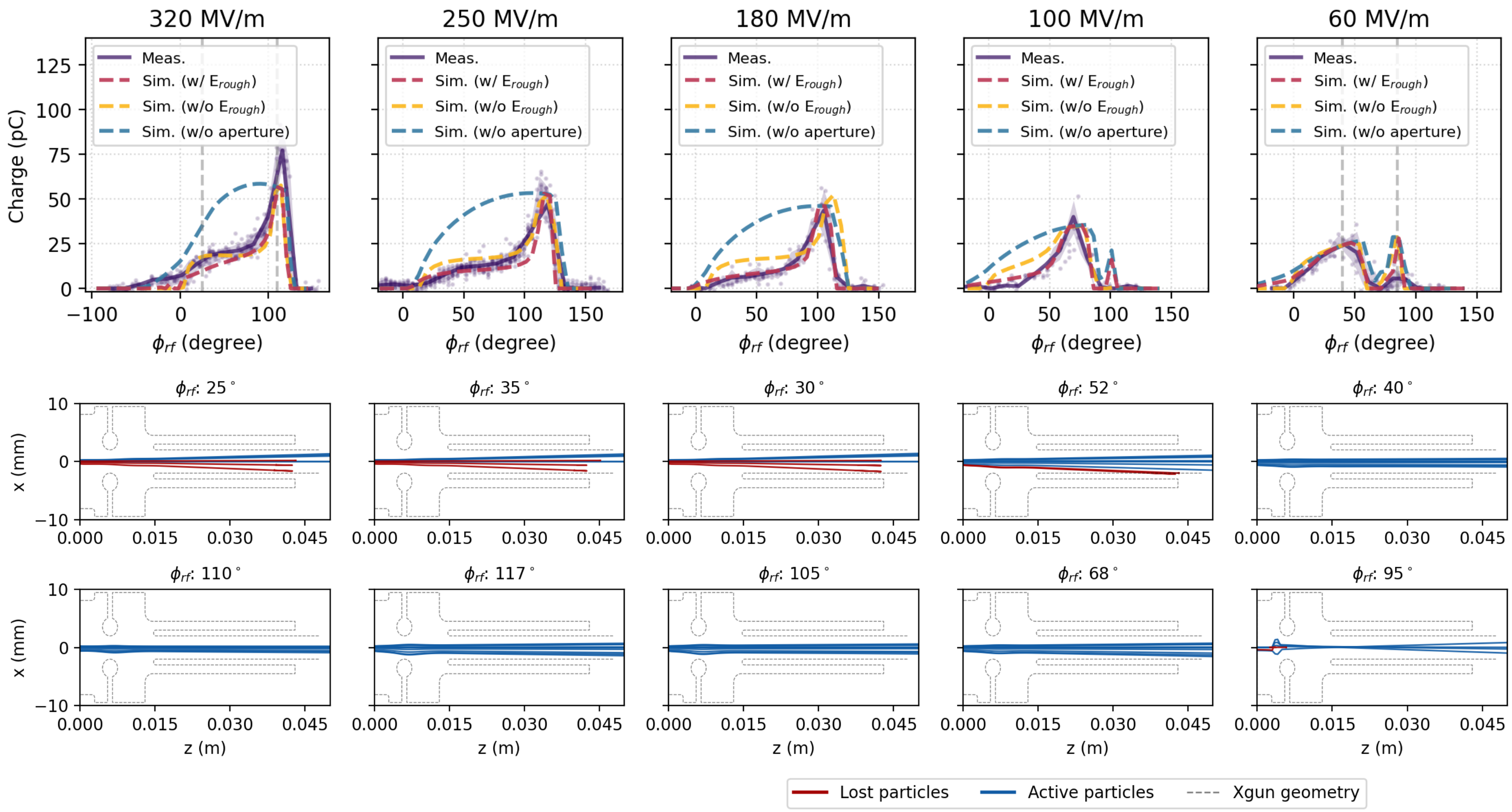
Scott Doran (AWA)
Seongyeol Kim (AWA)
Wanming Liu (AWA)
Alex Ody (AWA)
John Power (AWA)
Charles Whiteford (AWA)
Eric Wisniewski (AWA)
Gwanghui Ha (now at NIU)
Jiahang Shao (now at IASF)

Chunguang Jing (Euclid Techlabs / AWA)
Ernie Knight (Euclid Techlabs)
Sergey Kuzikov (Euclid Techlabs)
Pavel Avrakhov (Euclid Techlabs)
Sergey Antipov (now at PALM Scientific)

Emily Frame (NIU)
Xueying Lu (NIU / AWA)
Philippe Piot (NIU / AWA)
Wei Hou Tan (now at SLAC)

BACKUP

PHASE SCAN + BEAM TRAJECTORY



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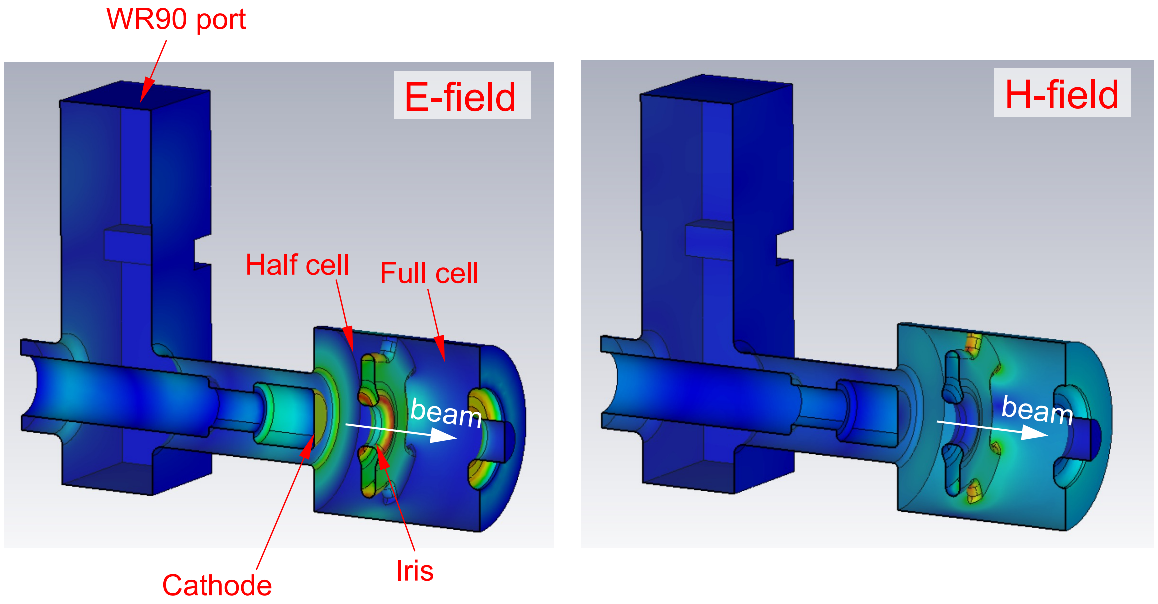
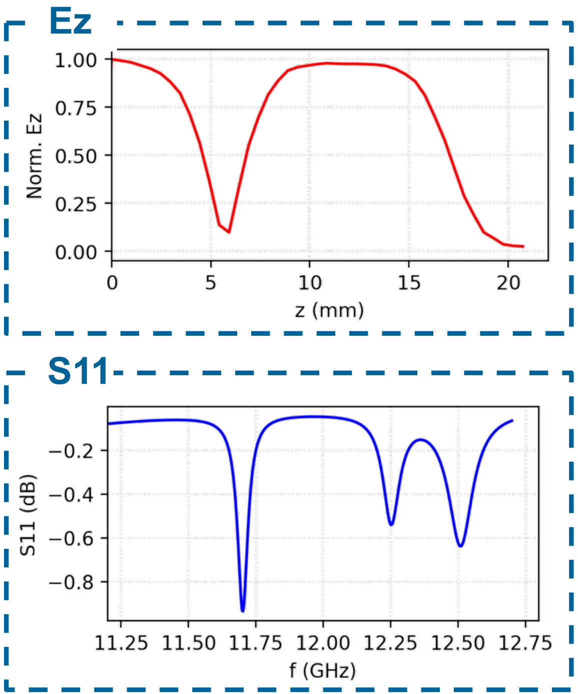
NEW XGUN DESIGN

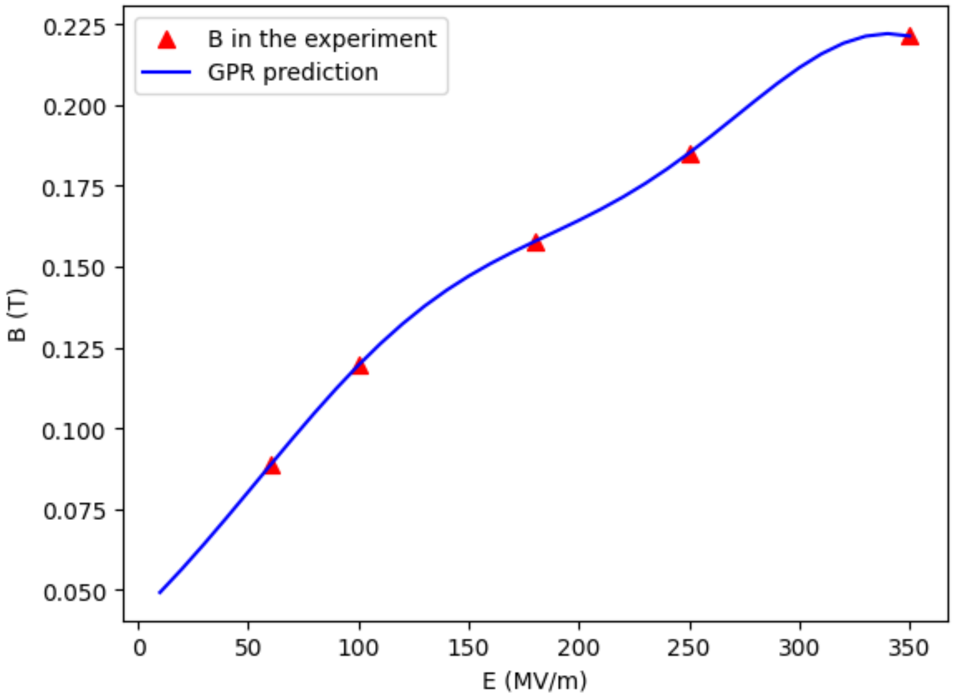
1.5 cell gun with removeable cathode

New Xgun is designed by Sergey Kuzikov and Ernie Knight at Euclid TechLabs.





MP SIMULATION



MP scanning:

- E:10, 20,…, 350 MV/m w/ predicted B @ each gradient level
    - Phi: 0, 10, …, 360 deg