Field emission study at Argonne Wakefield Accelerator facility (AWA)

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on behalf of many collaborators

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Outline

- Background and motivation
- L-band test stand at Argonne Wakefield Accelerator facility (AWA)
- Pin cathode experiment
- Dark current imaging experiment
- Summary and future study
- Acknowledgement

Background and motivation

- **Field emission**

  - Important in high gradient dc and rf devices, cold cathode electron sources, and internal electron transfer process in electronic devices [1]

  - Strongly coupled to the rf breakdown phenomenon, generally considered to be the trigger

  - Described by the Fowler-Nordheim formula: [2]

$$\overline{I_f} = \frac{5.7 \times 10^{-12} \times 10^{4.52\phi^{-0.5}} A_e (\beta E_0)^{2.5}}{\phi^{1.75}} \exp\left(-\frac{6.53 \times 10^9 \times \phi^{1.5}}{\beta E_0}\right)$$

E_0: usually taken as the externally applied field, or plus space charge effect

ϕ: usually considered to be constant for certain material

β and A_e: fitted parameters by a series of $\overline{I_f}$ and E_0, usually inconsistent with surface analysis [3,4]

1. R. G. Forbes and J. H. Deane, in Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, Vol. 463 (The Royal Society, 2007) pp.2907–2927.
2. J. W. Wang and G. A. Loew, SLAC PUB 7684 (1997).
3. H. J. Qian, et al., PRST-AB 15, 040102 (2012).
4. H. B. Chen, et al., PRL 109, 204802 (2012).

Background and motivation (continue)

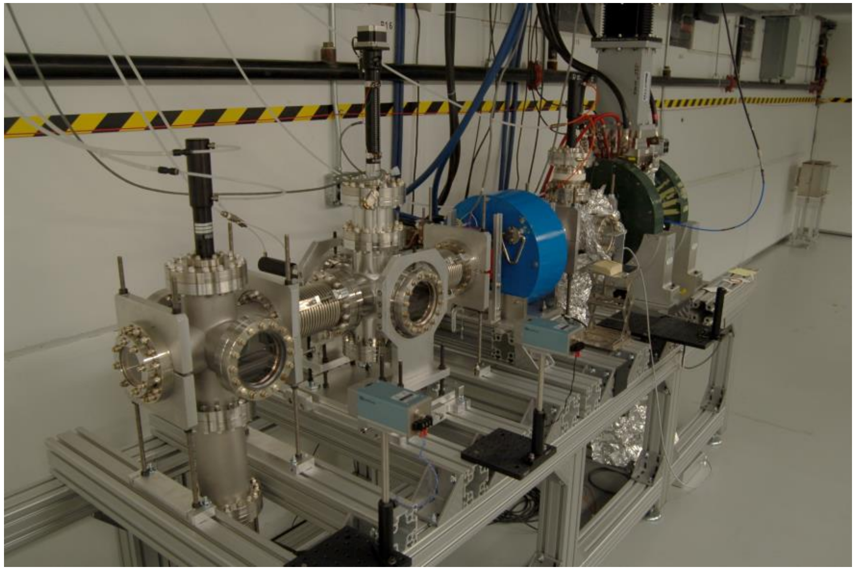
- **Only depends on externally applied electric field?**
  - Recent theory: microscopic field emission can couple to global parameters of a system (frequency, group velocity), self-induced field should be considered [1]
  - Travelling wave structure experiment: operational field strongly depends on the net power flow [2]
  - Investigation of field emission dependence on stored energy/ input power in a standing wave structure

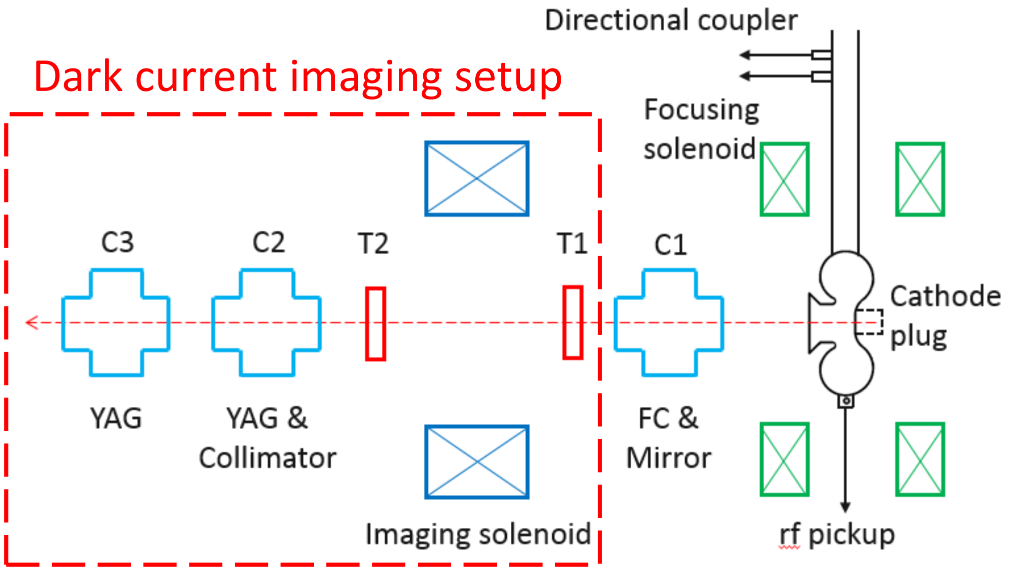
- **Where does strong field emission come from?**
  - DC imaging experiments: reveal different types of emitters [3,4]
  - RF imaging experiments: hard to locate emitters exactly due to broad energy spread
  - Develop a method to locate emitters in RF case

1. F. Wang, in Proceeding of 8th International Workshop on Breakdown Science and High Gradient Technology, Beijing, China (2015).
2. F. Wang and Z. Li, in Proceeding of the 4th International Particle Accelerator Conference, Shanghai, China, WEPFI083 (2013).
3. A. Dangwal, et al., J. Appl. Phys. 102, 044903 (2007).
4. V. Chatterjee, et al., Appl. Phys. Lett. 104, 171907 (2014).

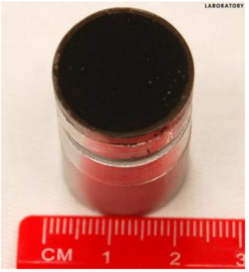
L-band test stand at AWA

- Single cell gun, 1.3 GHz
- 2 MW maximum input power





flat
(AWA) [1]



UNCD
(EUCLID) [2]

pin
(SLAC) [3]

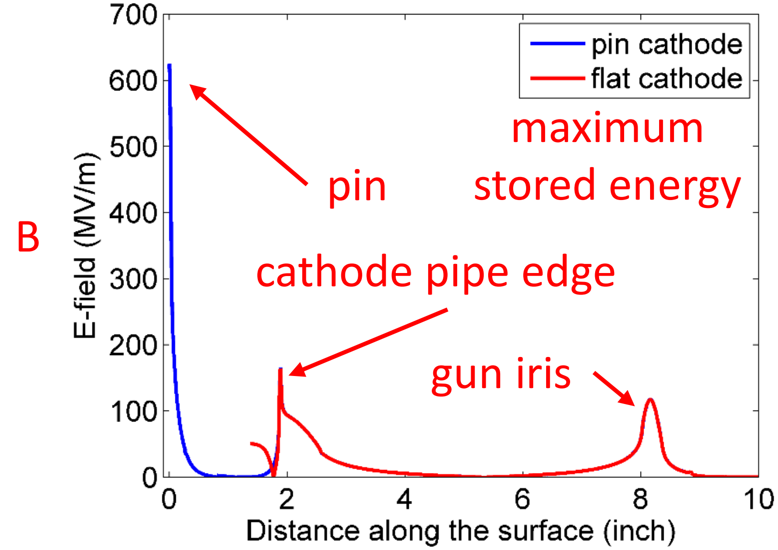
new shape
(Tsinghua) [4]

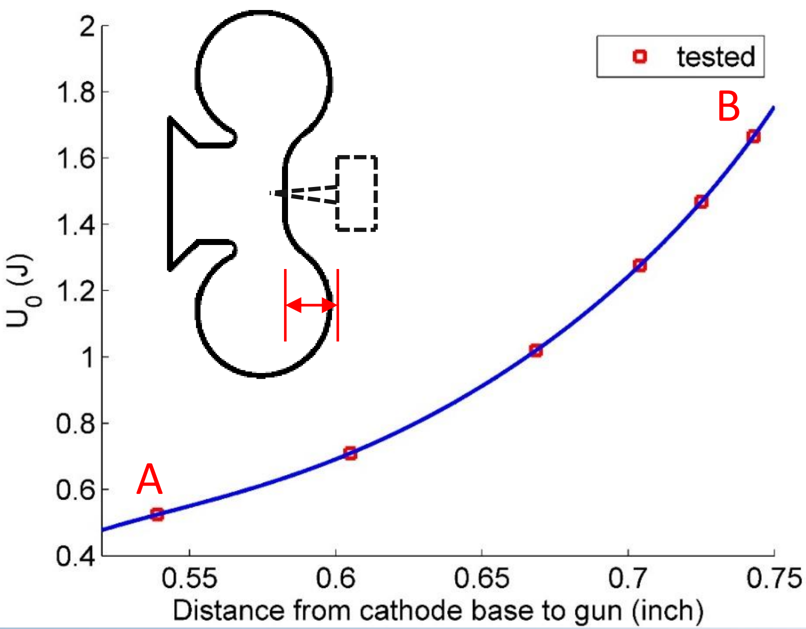
1. J. Shao et al., in Proceeding of the 6th International Particle Accelerator Conference, Dresden, Germany, THPRI077 (2014).
2. S. V. Baryshev et al., Appl. Phys. Lett. 105, 203505 (2014).
3. J. Shao et al., in Proceeding of the 6th International Particle Accelerator Conference, Richmond, VA, USA, WEPMN016 (2015).
4. J. Shao et al., in Proceeding of the 6th International Particle Accelerator Conference, Richmond, VA, USA, WEPMN015 (2015).

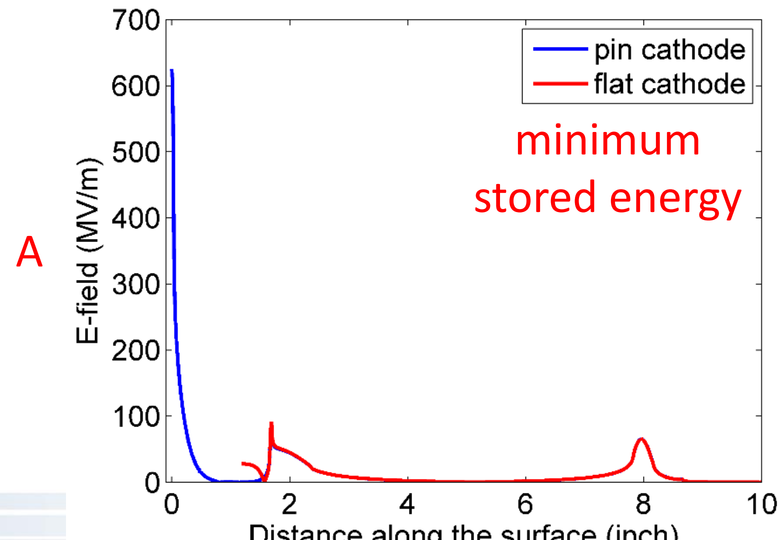
Pin cathode experiment

Cavity simulation

- Different stored energy for the same E-field on the tip (Etip) by adjusting the recess
- Compensate the detuning by a tuner at side of the gun







Experiment process

- Condition history

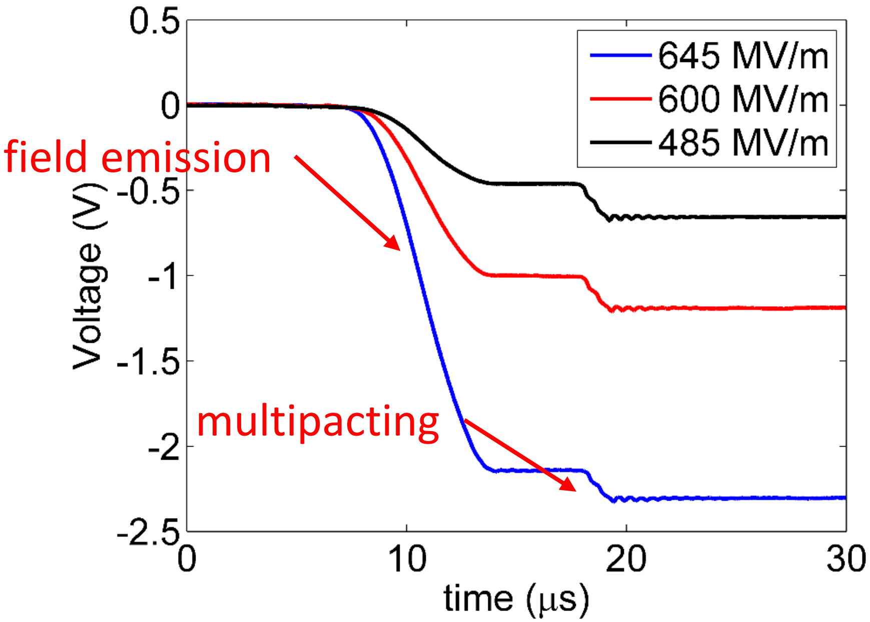
	No.07	No.15
pulse length (μs)	8.0	5.5
flat top of E-field (μs)	6.5	4.0
repetition rate (Hz)	10	2
total pulse	~190,000	~50,000
number of breakdown	~100	~30
maximum Etip (MV/m)	~ 700	

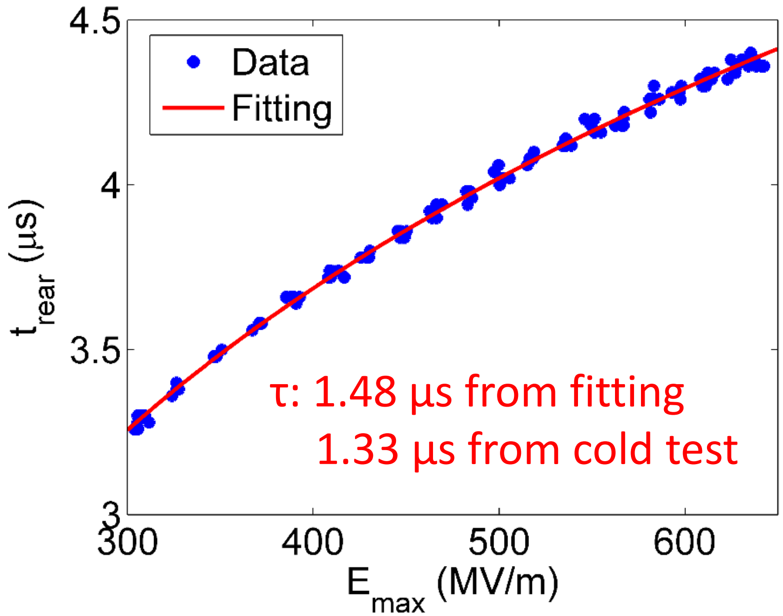
- During the measurement, the maximum Etip was lowered to ~660 MV/m to avoid breakdown and keep the same surface condition
- Scan focusing solenoid and input power for each cathode position
- Each cathode position took ~ 2 hours for the measurement
- Repeat measurement to confirm surface condition was not changed

Faraday cup signal

- Two steps observed in the Faraday cup (with integral circuit) signal: field emission and multipacting, only the first one is taken into account
- Multipacting verified by: 1) the amplitude of this step is independent with the input power; 2) the delay t_{rear} between the start of this step and the end of the rf pulse follows [1]

$$E_{MP} = E_{max}\exp(-t_{rear}/\tau)$$

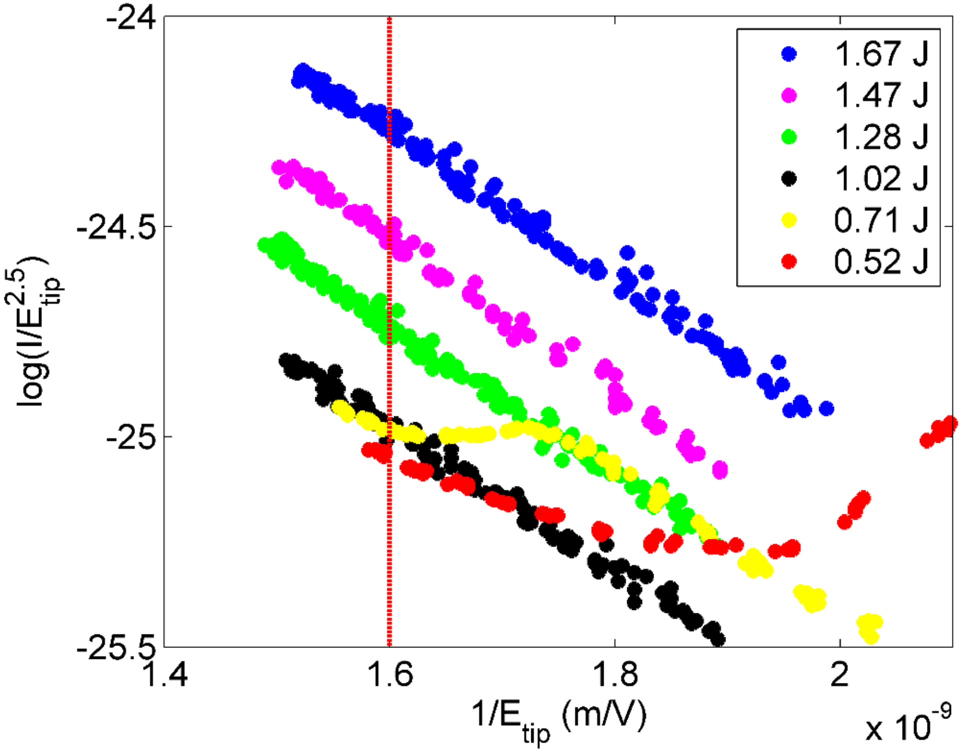




1. J. Han, K. Flöttmann, and W. Hartung, Phys. Rev. ST Accel. Beams. 11, 013501 (2008).

Fowler-Nordheim plot

- Higher stored energy leads to stronger dark current at the same Etip
- Nonlinear dependence at the low field end for the lowest two stored energies caused by multipacting at the beginning or during the rf pulse [1]
- Following data analysis based on Etip of 625 MV/m to minimize the influence from multipacting

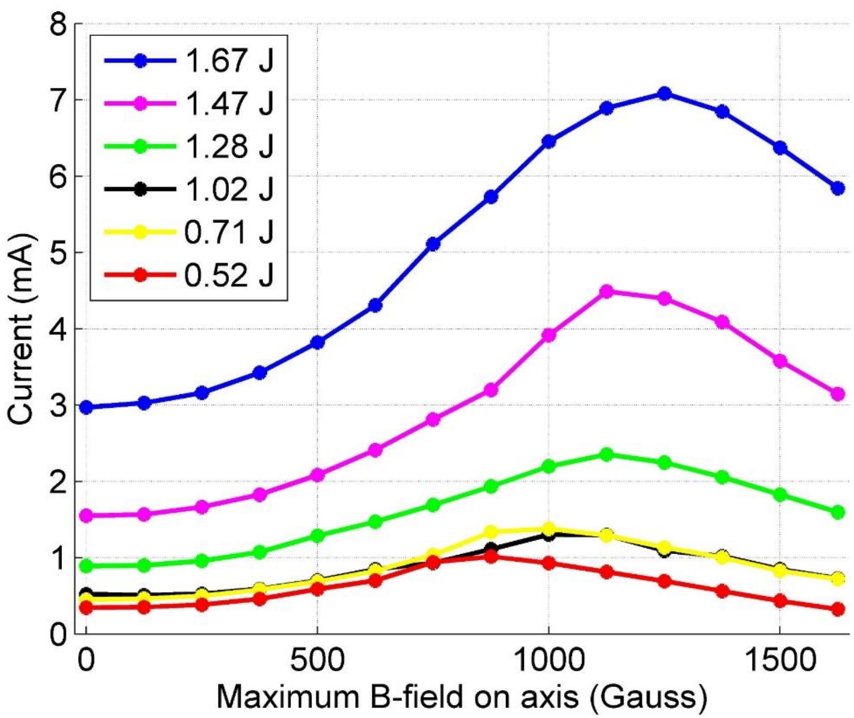


1. J. Han, K. Flöttmann, and W. Hartung, Phys. Rev. ST Accel. Beams. 11, 013501 (2008).

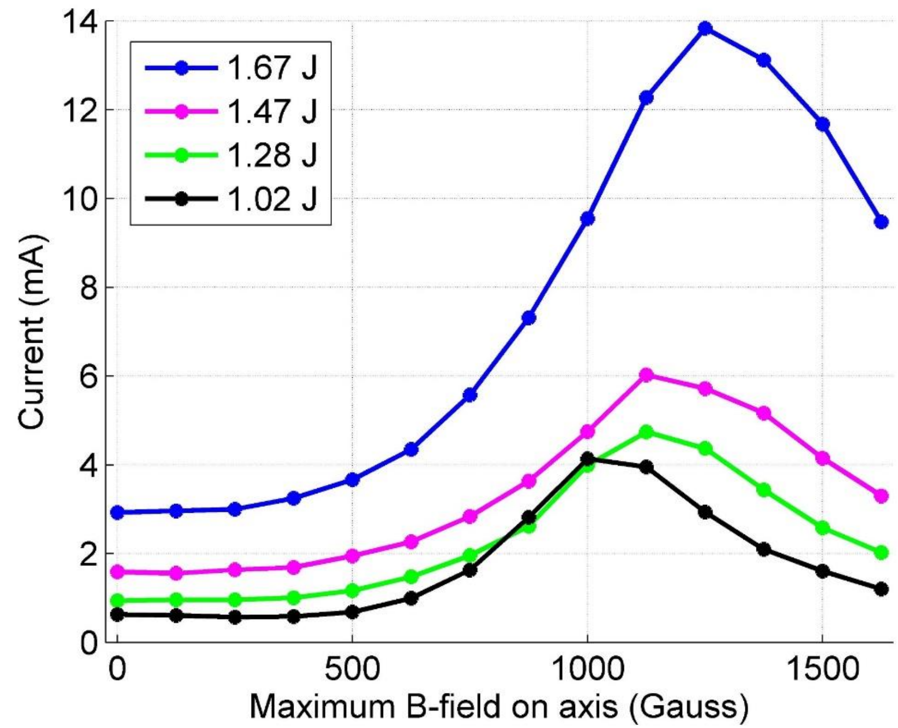
Experiment results

- During the experiment, the gun focusing solenoid was operated to capture the dark current efficiently

No.07 at E_{tip} of 625 MV/m



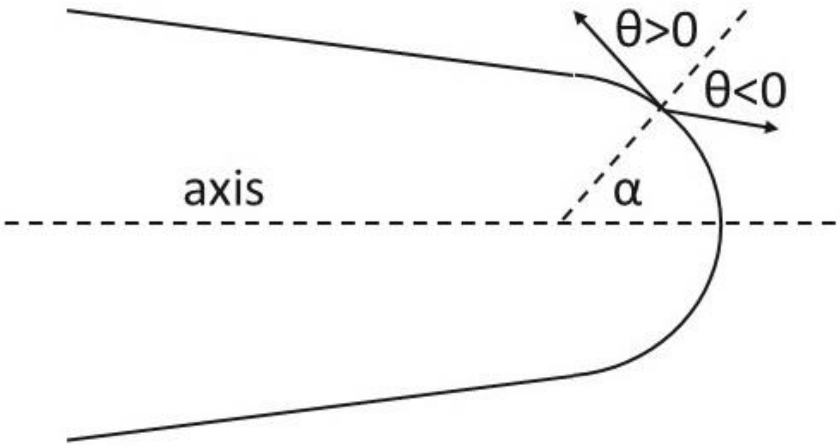
No.15 at E_{tip} of 625 MV/m



- The difference in current can be caused by the emission process and the transmission from the cathode to the Faraday cup

Dynamics simulation

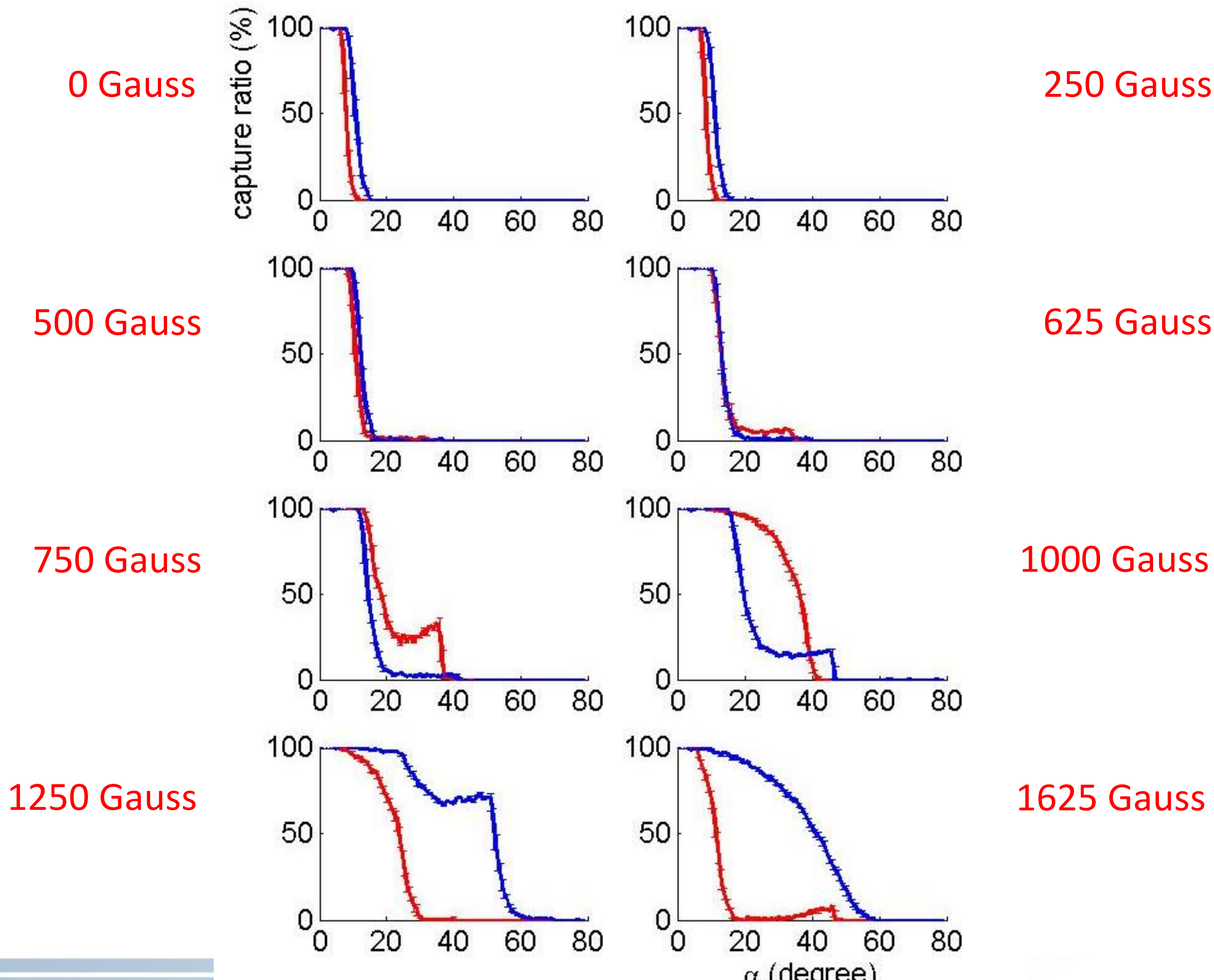
- ASTRA code [1] has been applied to study capture ratio at various stored energy and gun solenoid field with following assumption:
  1) the initial kinetic energy of the dark current is 7 eV (Fermi energy of Cu)
  2) the temporal structure of the emitted current is approximated by Gaussian distribution with β of 15 [2]
  3) space charge and mirror effect are not included (minor effect)



1. K. Flöttmann, ASTRA-A space charge tracking algorithm, DESY.
2. R. Huang, et al., Phys. Rev. ST Accel. Beams 18, 013401 (2015).

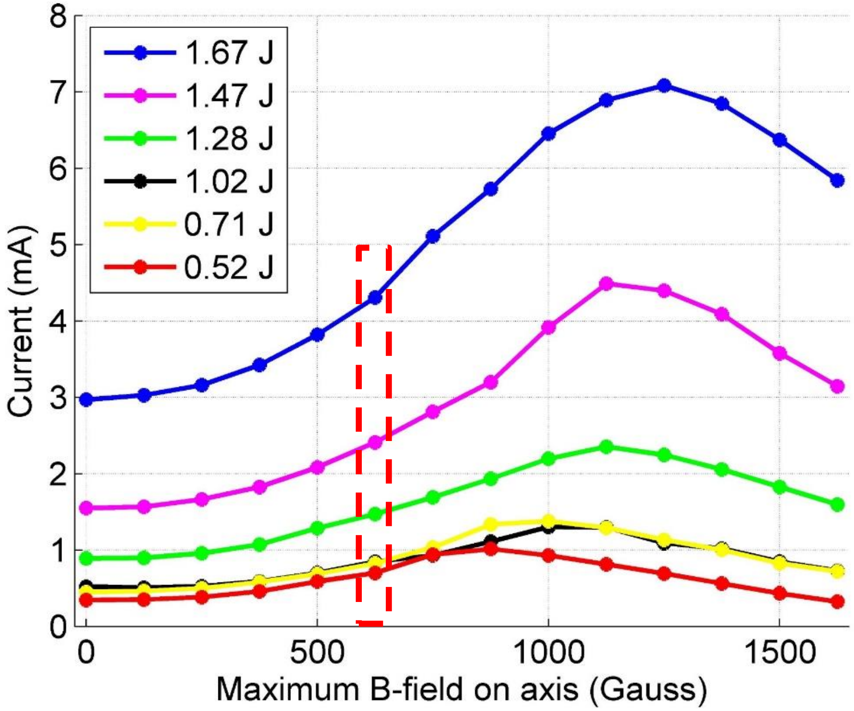
Dynamics simulation (continue)

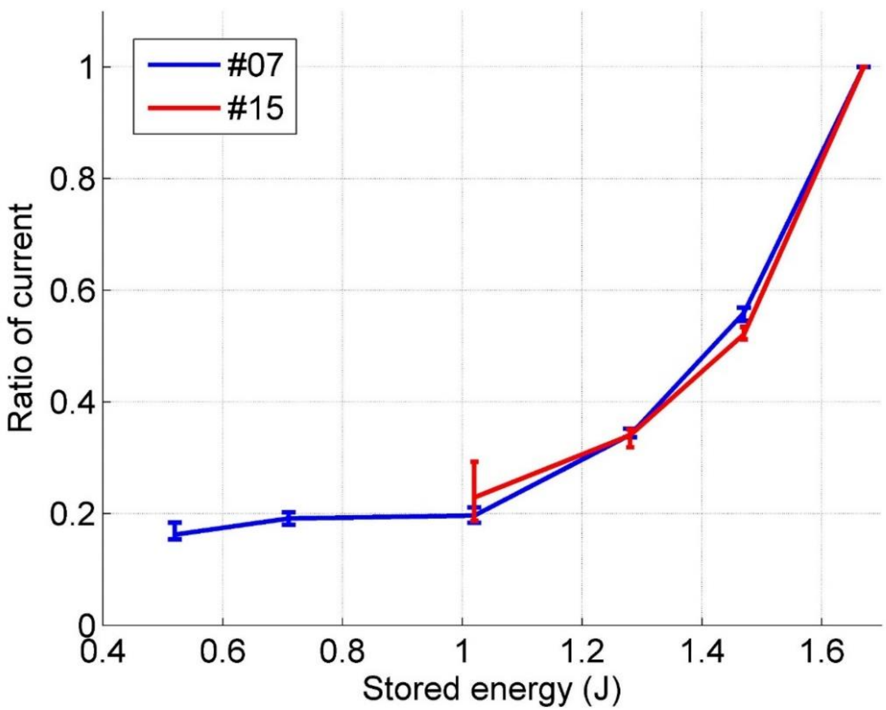
- Capture ratio vs. emission position (maximum and minimum stored energy)



Experiment results

- Five times difference in emission current when stored energy is varied by three fold
- Results of two identical pins agree very well with each other



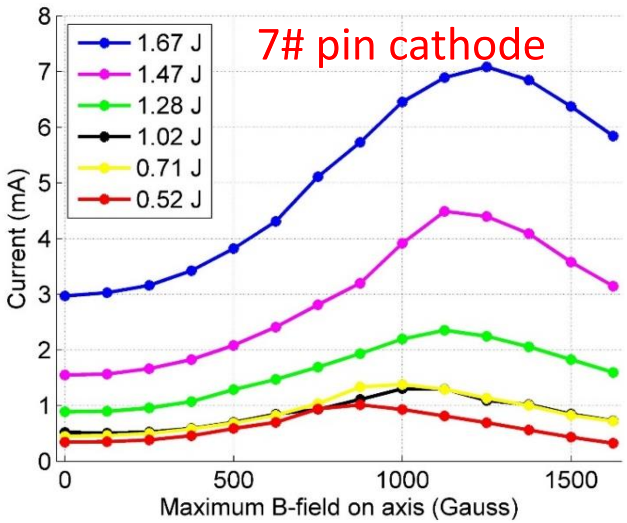


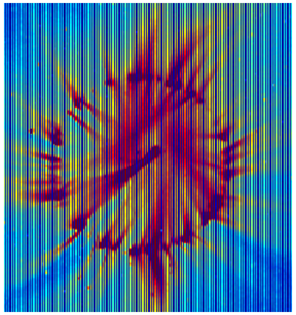
Against normal sense, why?

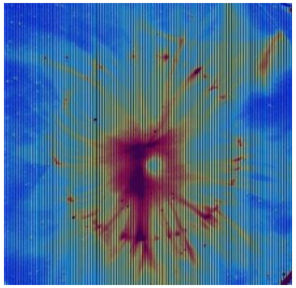
Discussion

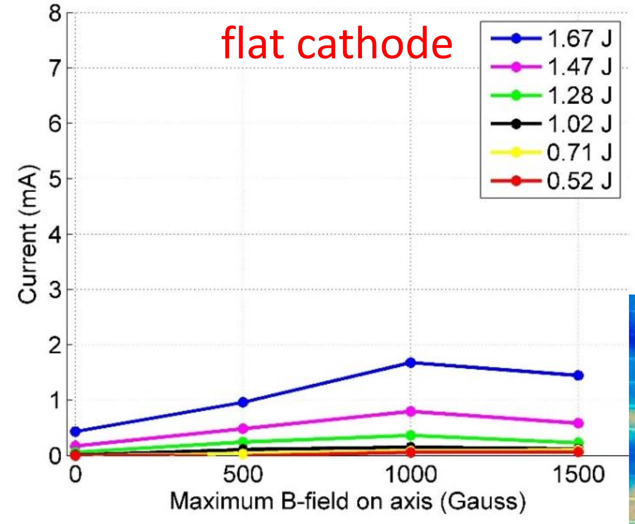
- Factors may contribute to this observation:

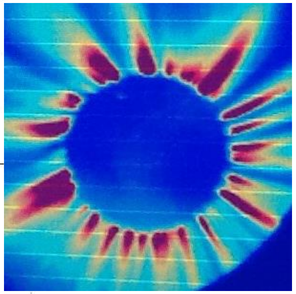
1. Emission from other parts of the gun (minor effect)

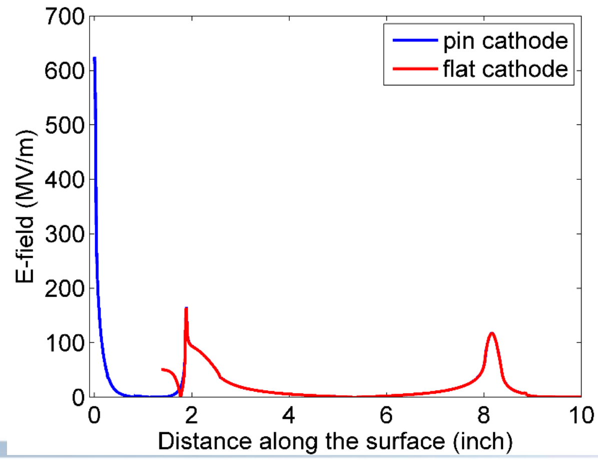


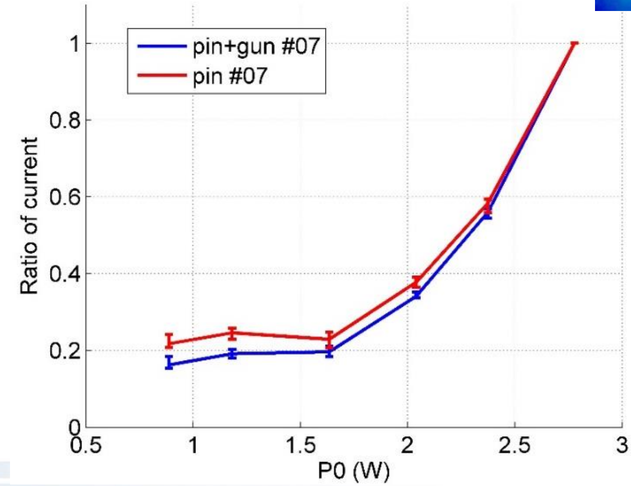












Discussion (continue)

- Factors may contribute to this observation:

2. Secondary electron yield (SEY) of the Faraday cup (minor effect) [1]

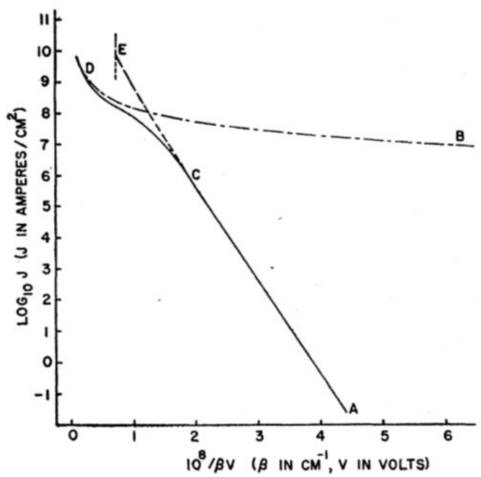
   SEY checked with up to 500 V DC bias applied onto the Faraday cup which leads to less than 5% correction

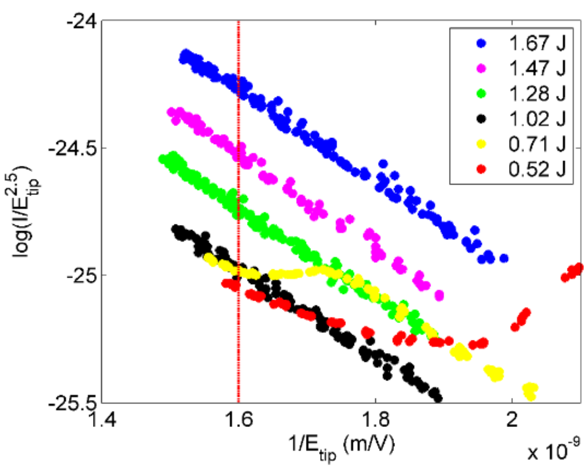
3. Beam loading (minor effect) [2]

   At the minimum stored energy, the beam power is less than 0.9 kW while the input power is ~350 kW

4. Space charge limited emission (minor effect) [3,4]

   Nonlinear dependence of $\log(I/E^2)$ on $1/E$ at high field has not been observed





1. J. S. Pearlman, Rev. Sci. Instrum. 48, 1064 (1977).
2. A. Chao, Handbook of accelerator physics and engineering (World scientific, 1999).
3. J. Barbour, W. Dolan, J. Trolan, E. Martin, and W. Dyke, Phys. Rev. 92, 45 (1953).
4. A. Rokhlenko, K. L. Jensen, and J. L. Lebowitz, J. Appl. Phys. 107, 014904 (2010).

Discussion (continue)

- Factors may contribute to this observation:

5. Self-induced field by the field emission current (possible mechanism) [3]

   - Local field is the sum of externally applied field and self-induced field by the emission current

$$E_s = E_a + \delta E$$

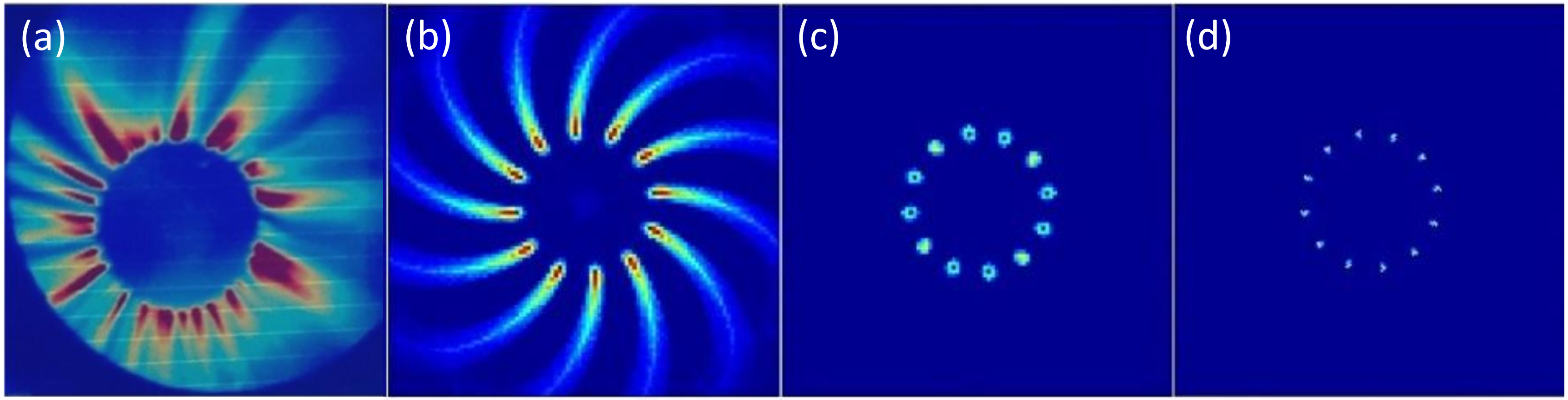
   - Self-induced field couples with global parameters of a system (stored energy)

1. F. Wang, in Proceeding of 8th International Workshop on Breakdown Science and High Gradient Technology, Beijing, China (2015).

Dark current imaging experiment

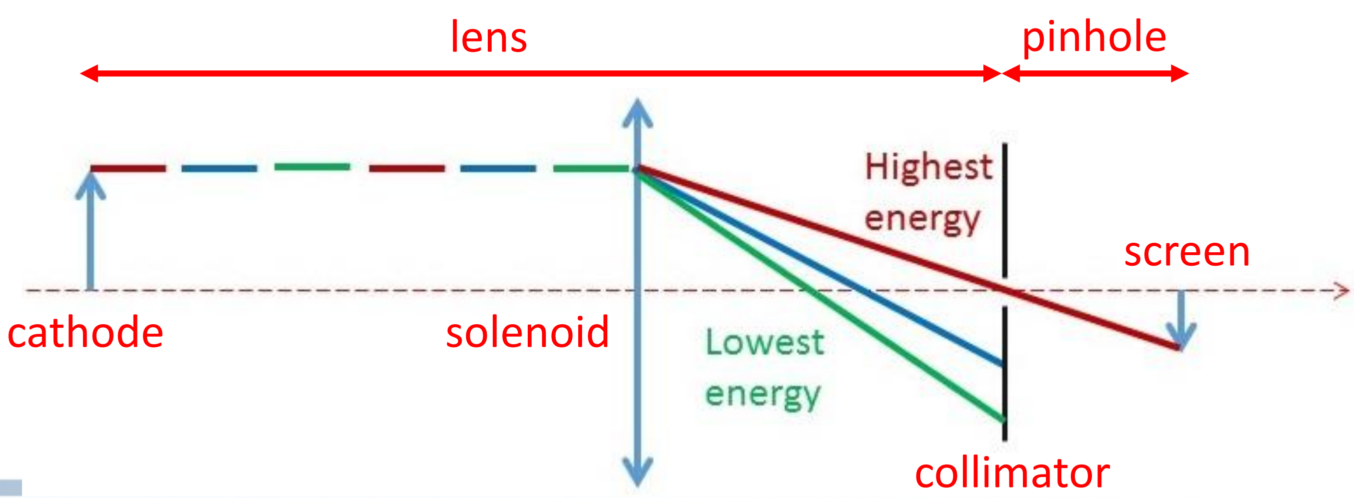
Imaging principle

- The difficulty of dark current imaging: the broad energy spread and various trajectory of electrons from a single emitter
- Solution: choose electrons with certain energy from the whole distribution



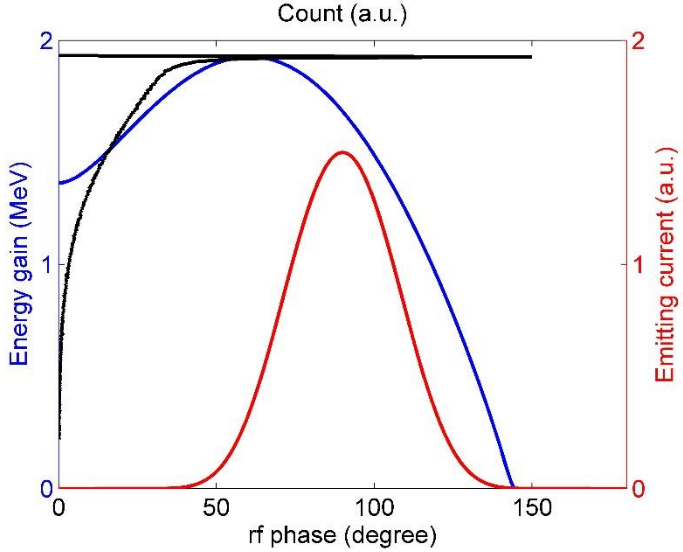
(a)experiment

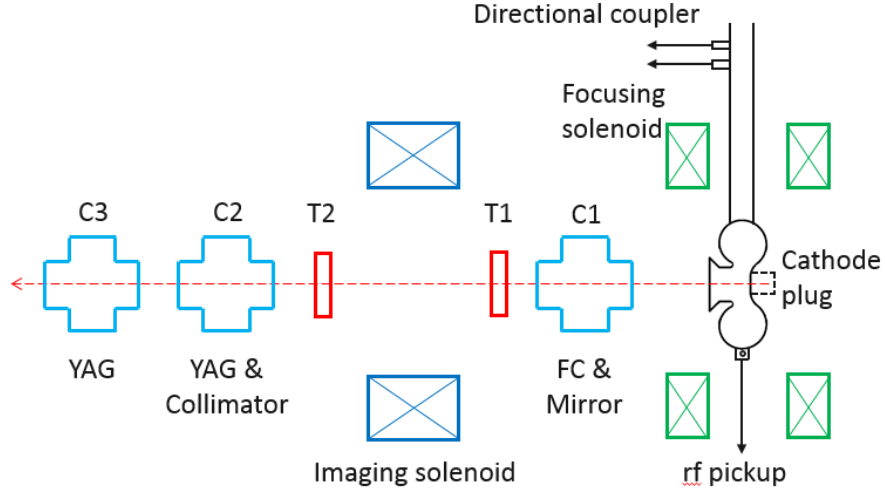
(b-d) simulation

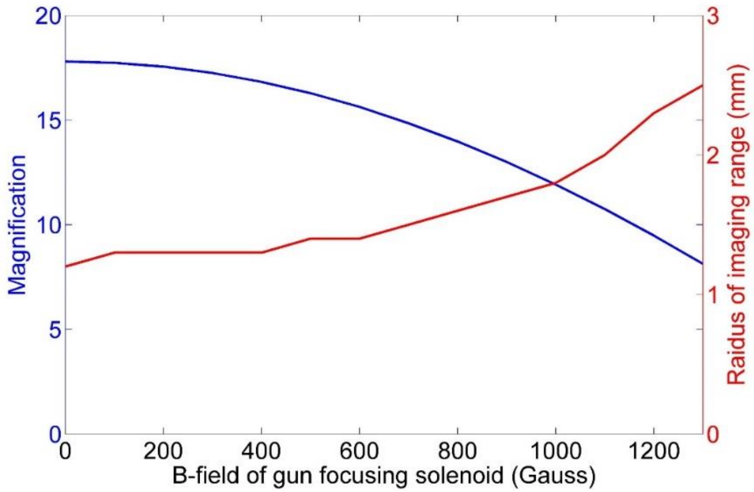


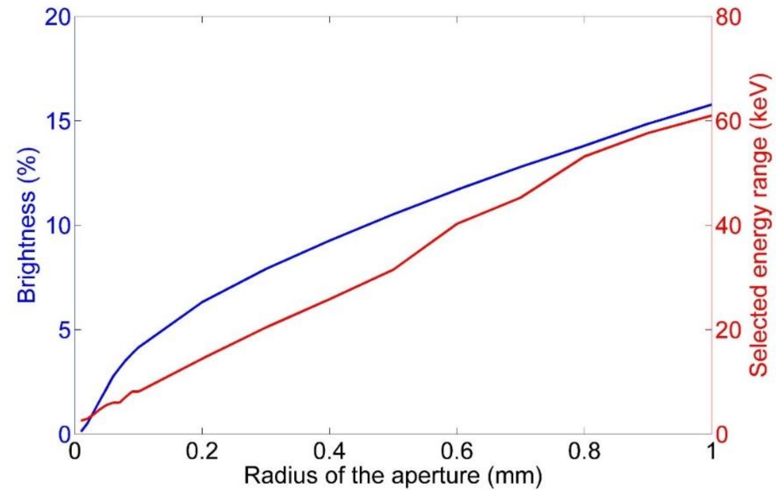
Dynamics study

- Electrons with the highest energy are chosen to maximize the image brightness





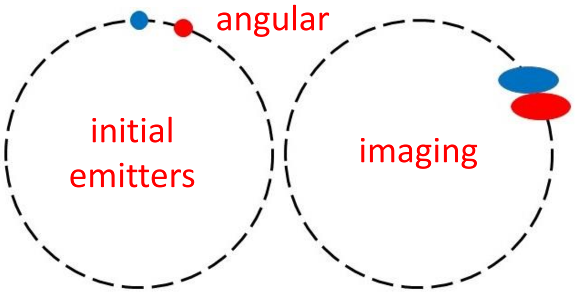


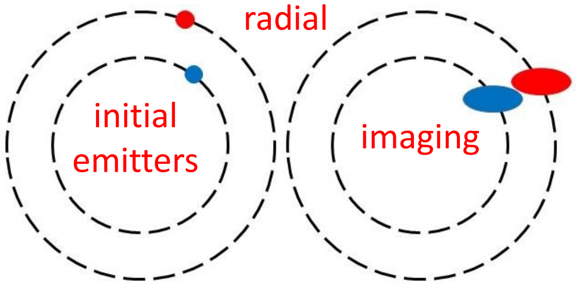


- Magnification and range of image can be adjusted by the focusing solenoid strength

Dynamics study (continue)

- The resolution can be further classified as angular and radial ones because of axial symmetry of the system

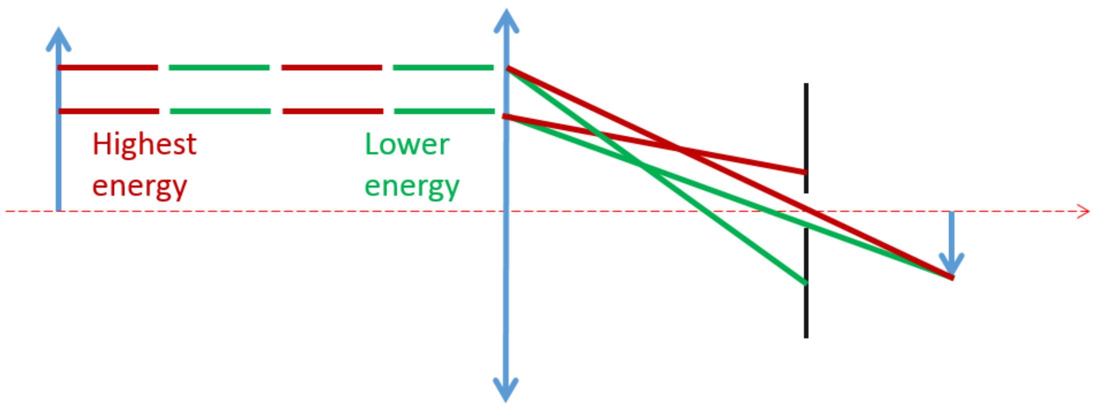


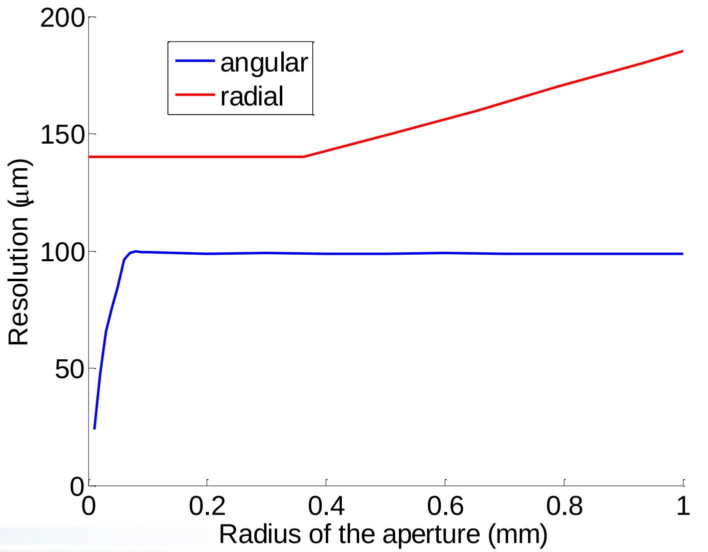


$$R_\theta = 2 \times rms(\theta') \times r$$

$$R_r = \min(r_{B,0} - r_{A,0}), r_B - r_A \geq rms(r_A) + rms(r_B)$$

Limited radial resolution caused by the spherical aberration of the system



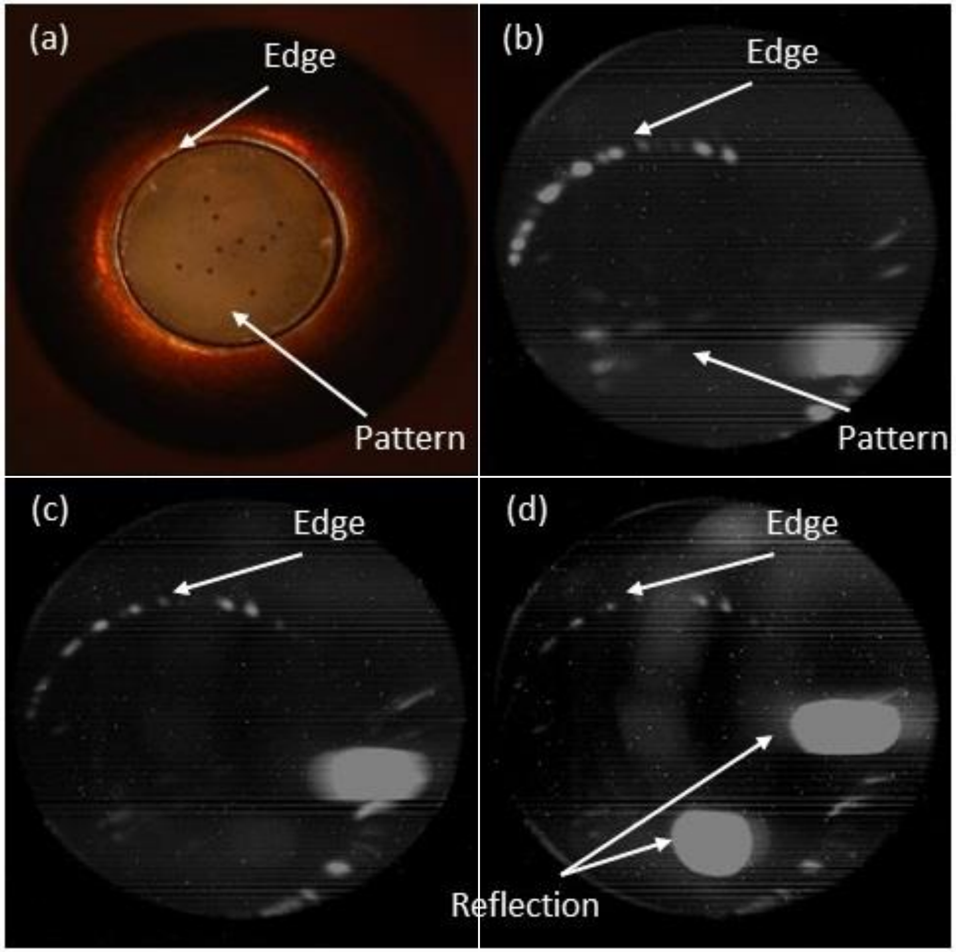


The first experiment

- Successful demonstration of the dark current imaging principle in rf guns
- More improvement in forthcoming experiments

initial emitters

0.25 mm aperture radius

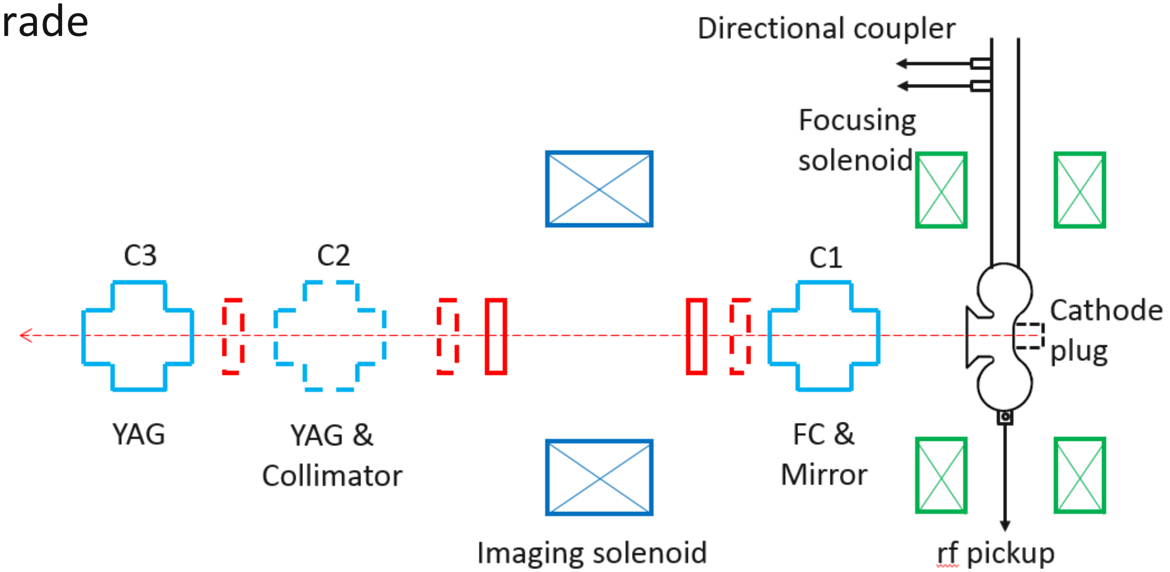


0.17 mm aperture radius

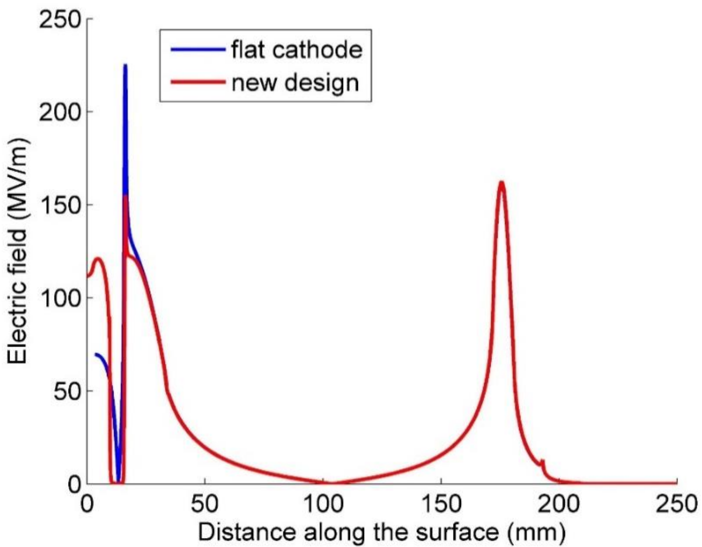
0.10 mm aperture radius

Future experiment improvement

- Beam line upgrade



- New shape cathode to enhance field on the cathode and suppress field on the pipe edge



Summary and future study

- **Conclusion**

  Pin cathode experiment:

  - Vary the stored energy while keeping the same E-field on tip by adjusting the cathode recess

  - Strong correlation between field emission and the stored energy

  Dark current imaging experiment:

  - Use collimator to select electrons with certain energy

  - Preliminary experiment reveals emitters on the cathode pipe edge

- **Future study**

  - Theoretical study of stored energy dependence

  - Test more cathodes with predefined emitters with improved dark current imaging system

  - Surface analysis of emitters

Acknowledgement

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- All staffs in AWA group for their great help and support for experiments

- SLAC machine shop for preparing pin-shaped cathodes, Tsinghua machine shop for preparing new-shaped cathode

- Dr. Klaus Floettmann for discussing about ASTRA simulation

Thanks!