Studies on Factors Affecting the Life-time of High Average Current GaAs Photocathode*

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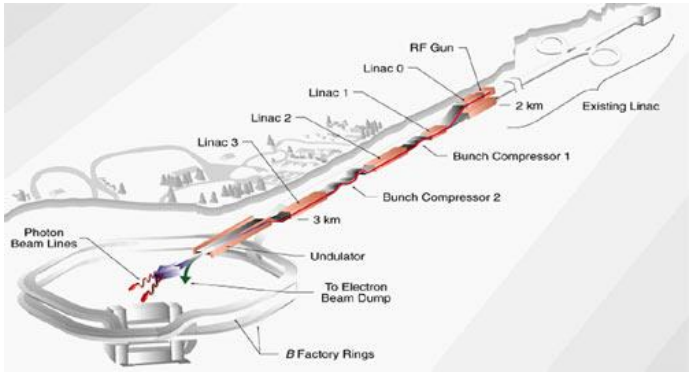
Outline

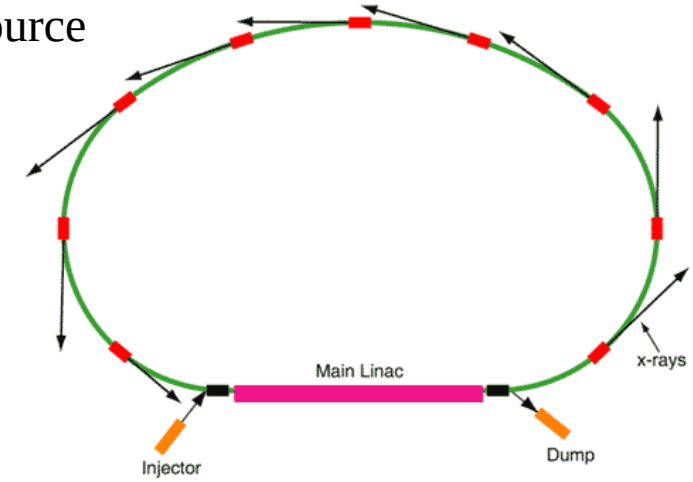
- 1. Background Introduction
- 2. Physical Model
- 3. Experiment Progress
- 4. Summary
- 5. Further studies

1.1 Background—①FELs&ERLs

Synchrotron light source



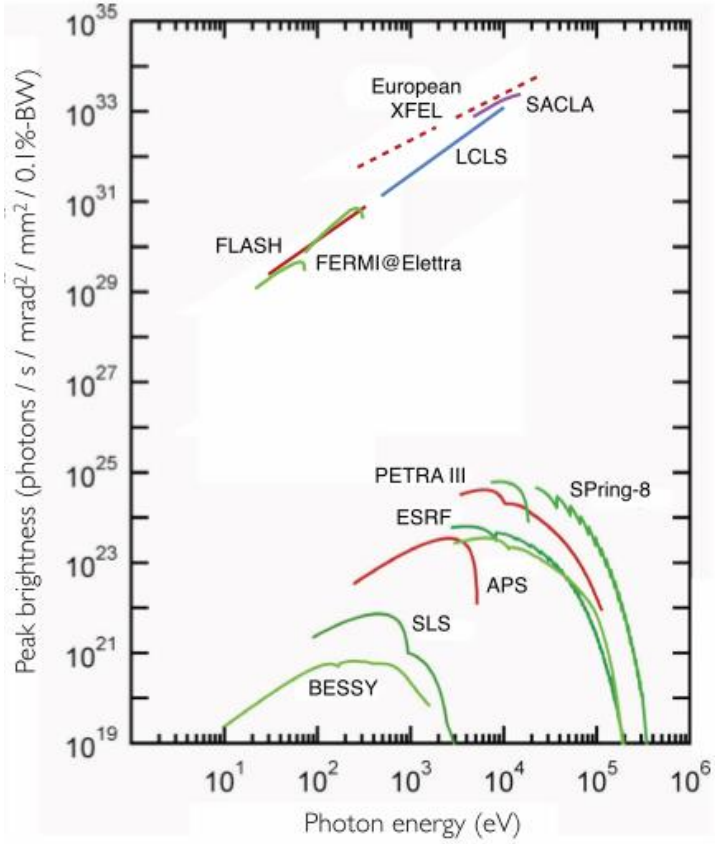
Free electron laser



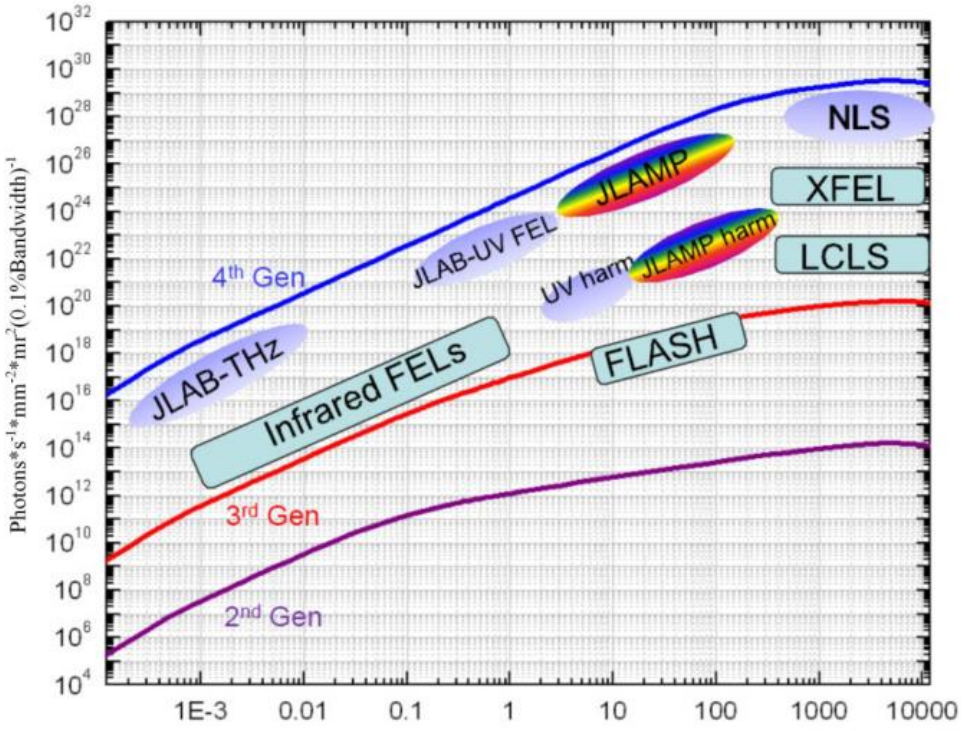
High average power FEL & ERL

Emma P, et al. nature photonics, 2010, 4(9):641–647.
Pile D. Nature photonics, 2011, 5(8):456–457.

② High repetition high-brightness



Peak brightness development



Average brightness development

Future:
injector with high average power high brightness !

Huang Z R. IPAC'13. 2013:16-20
Neil G R. Oral presentation of PAC'11, 2011

③Typical injectors

	JLab FEL[65]	Cornell ERL[25]	Boeing[58]	LBNL APEX[17]	WiFEL[59]	Rossen –dorf[63]	PKU[29]
	HV DC		NC RF		SC RF		DC-SRF
f/MHz	1497	1300	433	187	200	1300	1300
R_e/MHz	74.85	1300	27	187	200	1300	81.25
E_c/MV·m^{-1}	4	8	N/A	19.5	40	8	15
E_k/MeV	0.5	0.5-0.75	5	0.5	4	3	5
Cathode	GaAs	GaAs CsK_2Sb	CsK_2Sb	CsK_2Sb Cs_2Te	Cs_2Te	Cs_2Te	Cs_2Te
λ_l/nm	527	527	527	526 263	266	262	266
ε_n/μm	<7	<1	~7	<1	N/A	N/A	2.1
Current goal/mA	1000	100	1000	100	1	500	5
Achieved I_{max}/mA	> 10	60	32	0.3	N/A	0.018	0.27
Life-time at I_{max}	> 50h	~25min	N/A	4天	N/A	N/A	N/A
Status	working	working	retired	working	constructing	working	working
Main Problems	ions, field emission temperature		temperature , vacuum		temperature SC pollution		laser power cathode

Hernadez-Garcia C, ERL workshop,2009; Dunham B, et al. APL, 2013, 102(3):034105; Dowell D, APL, 1993,63(15): 2035-2037; Sannibale F, et al. IPAC'13:709-713; Legg R, et al. IPAC'12; Kong S,et al. JAP, 1995,77(11):6031-6038

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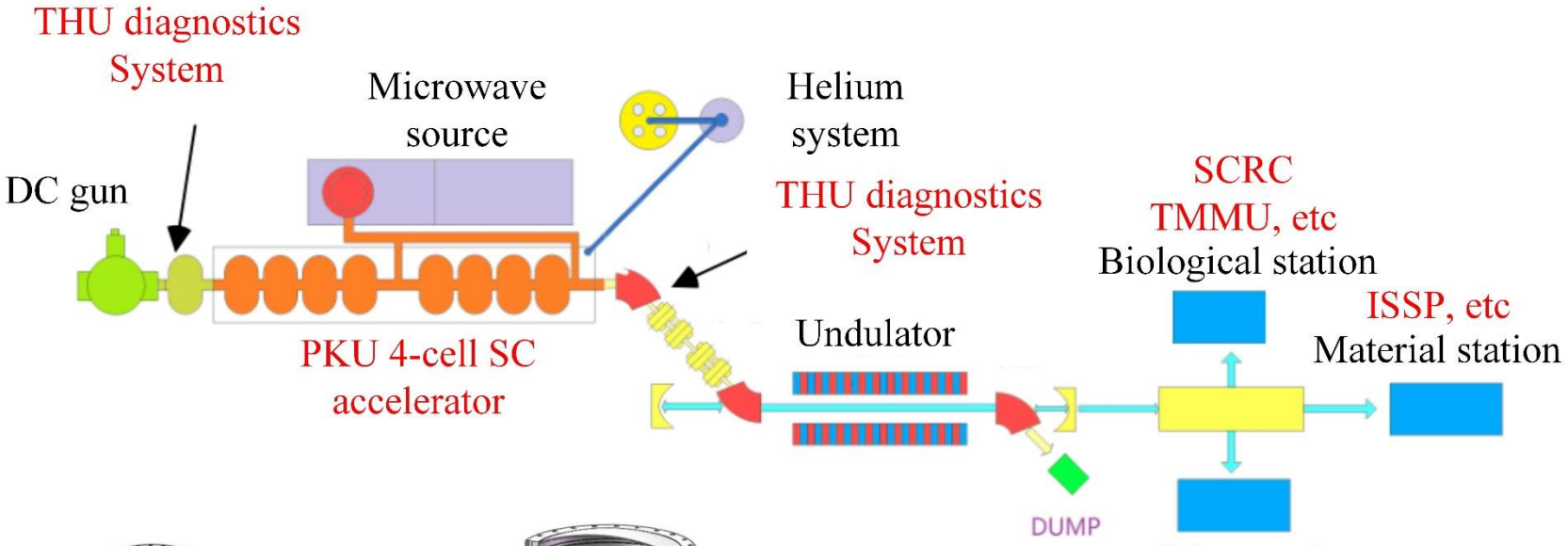
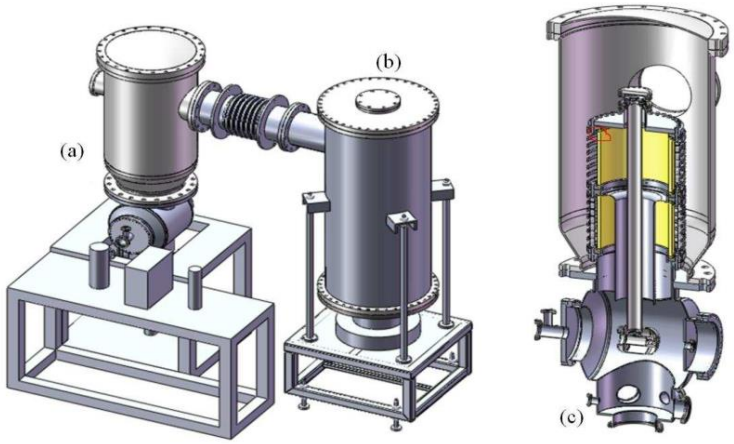
1.2 National Key Scientific Instrument and Equipment: FEL-THz



Layout of FEL-THz



HV DC photocathode gun

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Xu Z. Journal of Terahertz Science and Electronic Information Technology, 2013, 11(1):1-6

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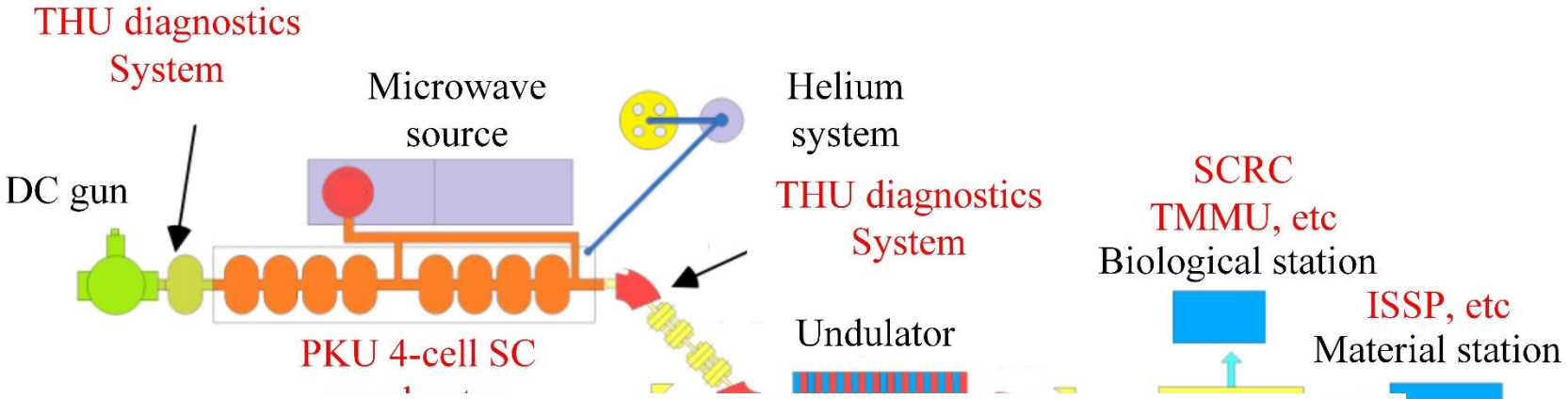
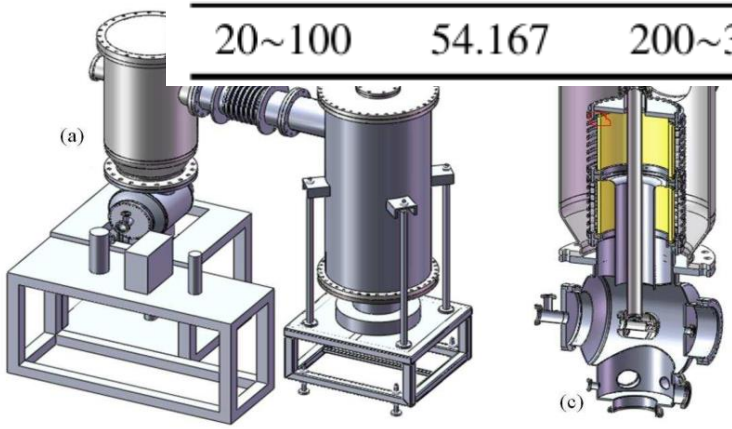


Charge /pC	Repetition /MHz	E_k /keV	Operation time /h	ε_n /mm·mrad	σ_t /ps
20~100	54.167	200~350	>?	<5	~20



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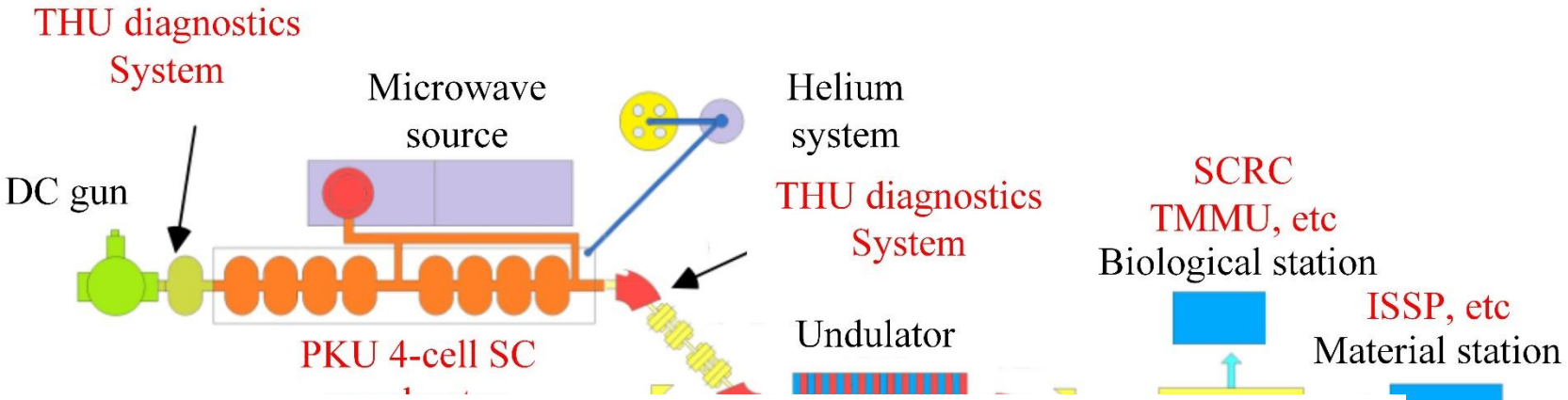

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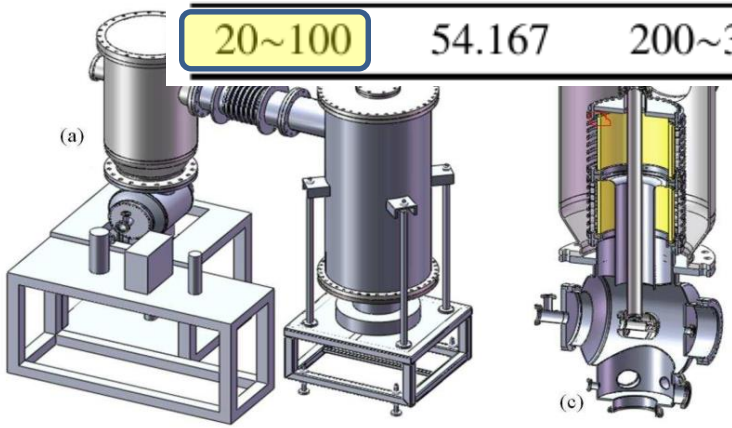

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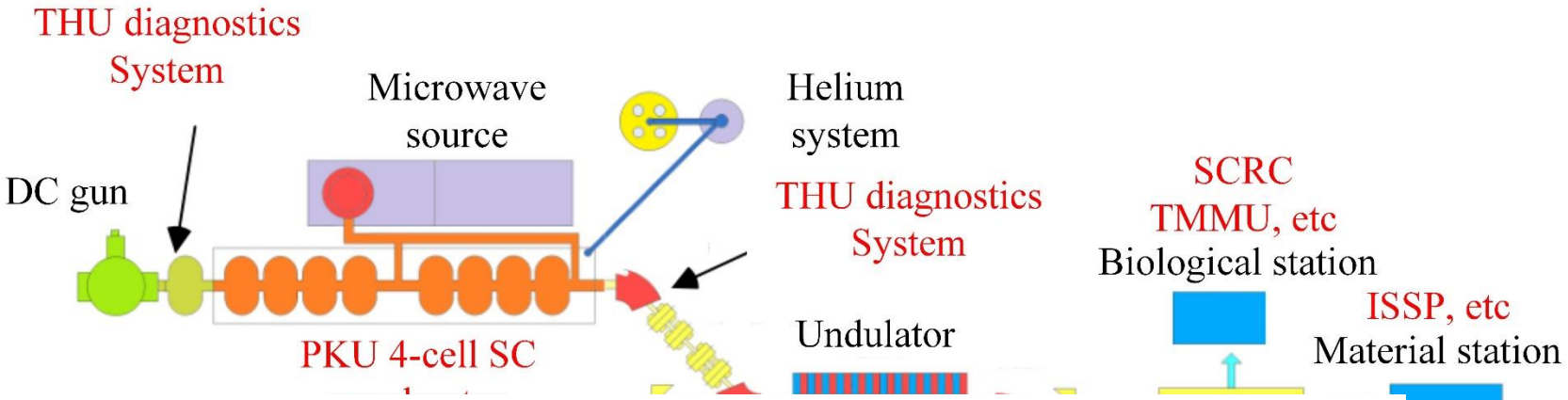

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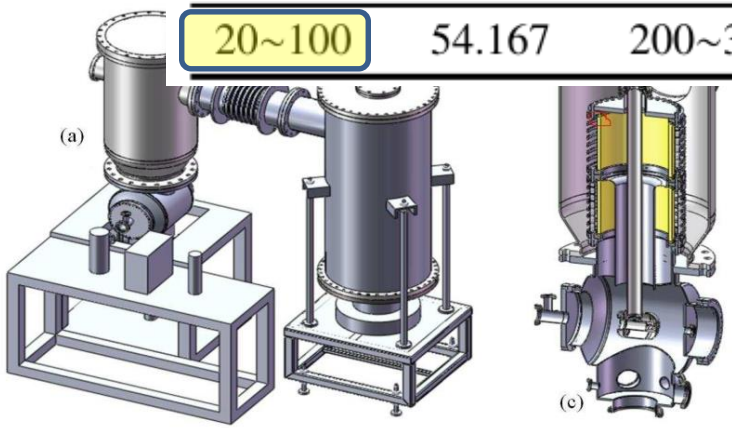

HV DC photocathode gun

The primary physical problem:

Stable long-life photocathode!

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1.3 Materials of photocathode

	Metal	Sigle-alkali	Multi-alkali	NEA
Typical Material	Cu	Cs_2Te	CsK_2Sb	GaAs
Vacuum/Pa	-7	-7~-8	-8~-9	-9~-10
QE	10^{-4}~10^{-5}	~0.1	~0.1	0.15
Work function/eV	>4	~3.5	~2.1	~1.5
Spectrum	UV	UV	UV—Visible	UV—Infrared
Advantages	Fast response，long life	Fast response	Fast response	Large amont of charge, polarization
Disadvantages	UV response	UV response	Pollution, short life	Ultrahigh vacuum, pollution, slow response
Applications	Low repetition injector	SC Gun NC RF gun	NC RF gun DC gun	DC gun

Qian H J, PHD Thesis, THU, Beijing, 2012; Dowell D, et al. NIMA.2010. 622(3):685-697; Sinclair C K. NIMA. 557(1):69-74; Bazarov I, et al. JAP, 103(5): 054901

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1.4 Research status of GaAs life-time

Vacuum

- Empirical formula $\tau = \tau_0 (p/p_0)^{-1.01}$

Ion back-bombardment

- No proper model

Temperature

Approximate $\frac{1}{\tau_d} = \frac{1}{\tau_{td}} + \frac{1}{\tau_c}$ $\tau_{td} = \exp(E_a/k_B T)/\nu$

Durek D, et al. Applied surface science. 1999, 143(1):319-322; 徐江涛. 应用光学. 1999, 20(2):6-9;
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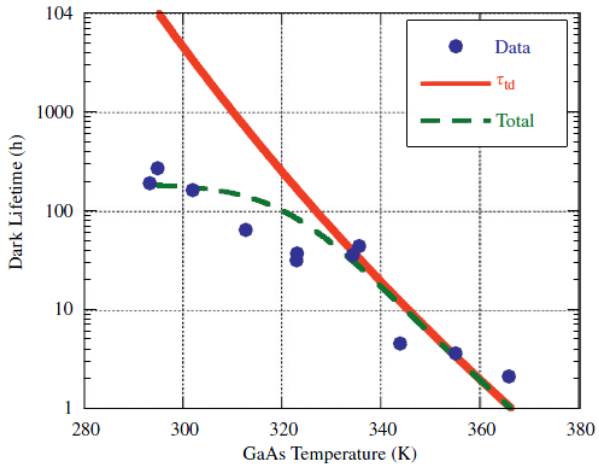

Life-time versus temperature

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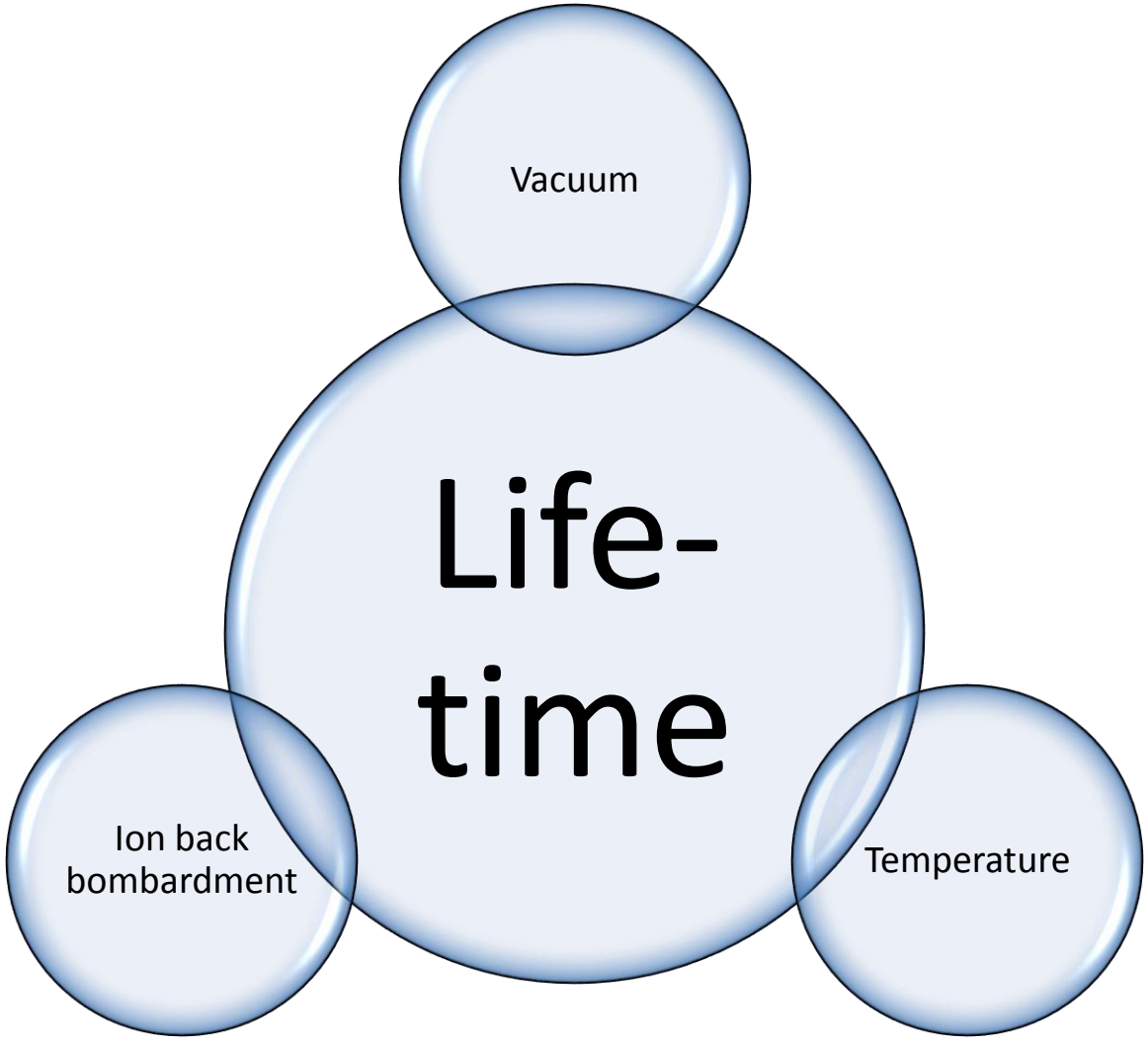
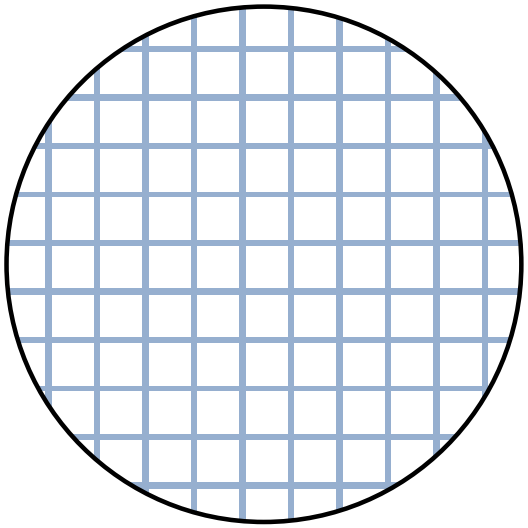
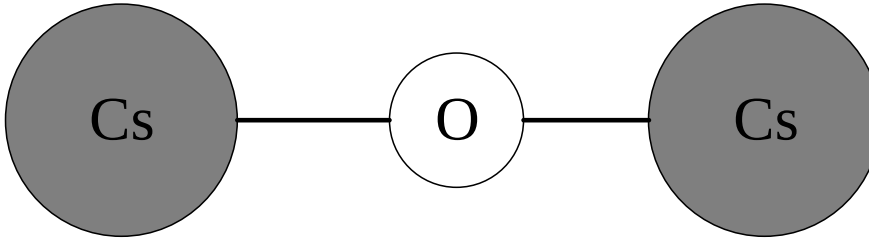


Physical process

GaAs
photocathode





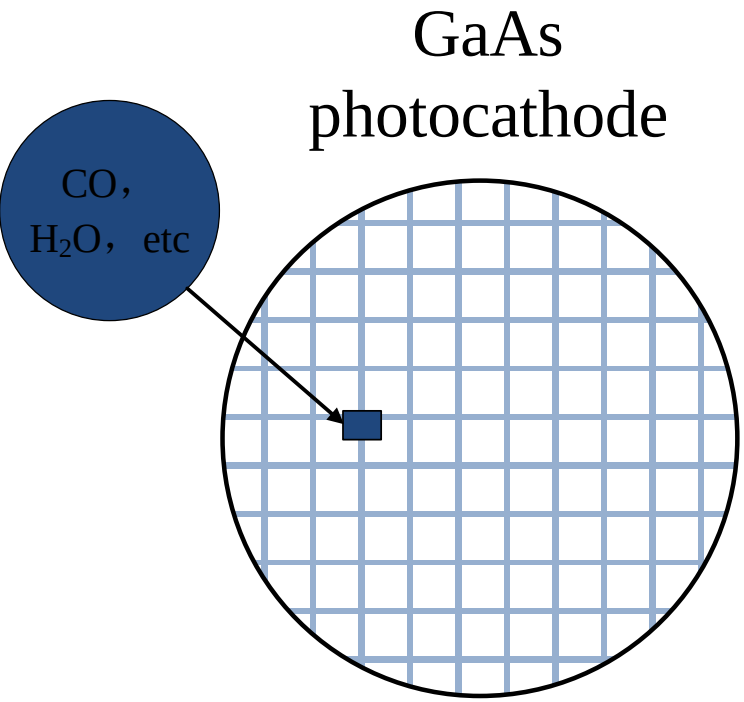
Number of activated regions: m

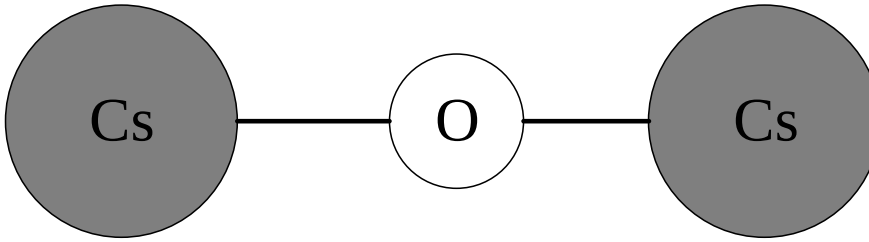
Ratio: $\theta(t)$

$$\theta(0) = 1, \eta(t) = \eta_0\theta(t)$$

$$I(t) = I_0\theta(t)$$

Physical process





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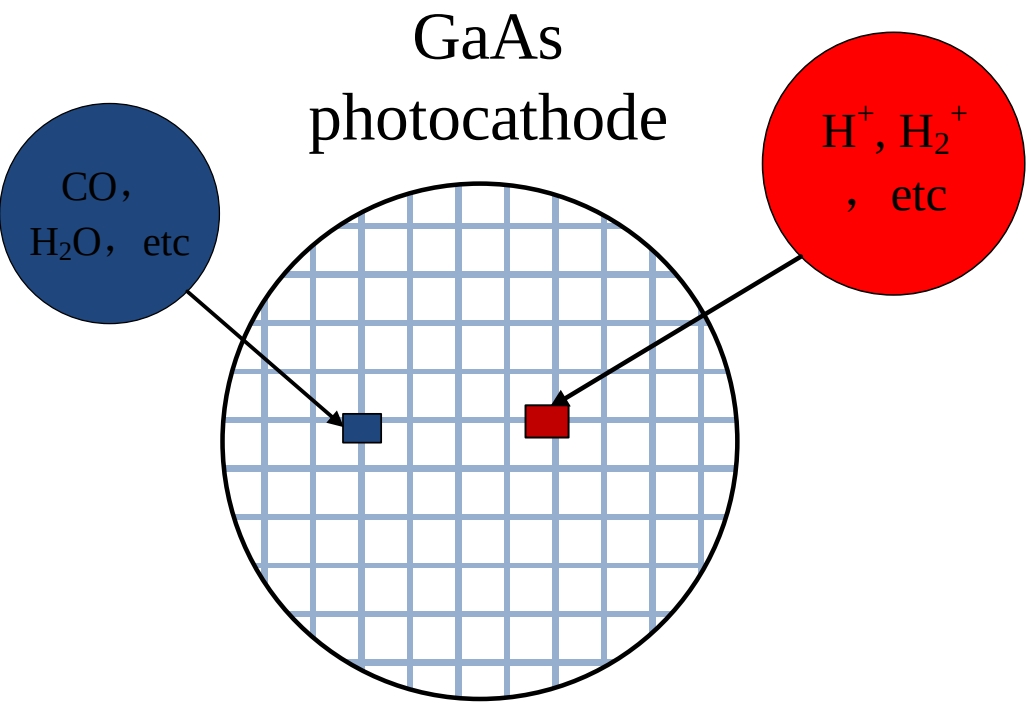

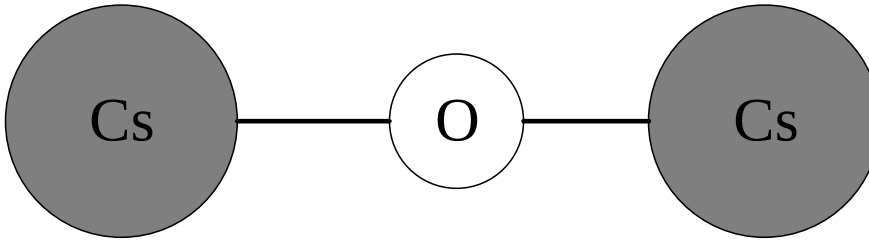

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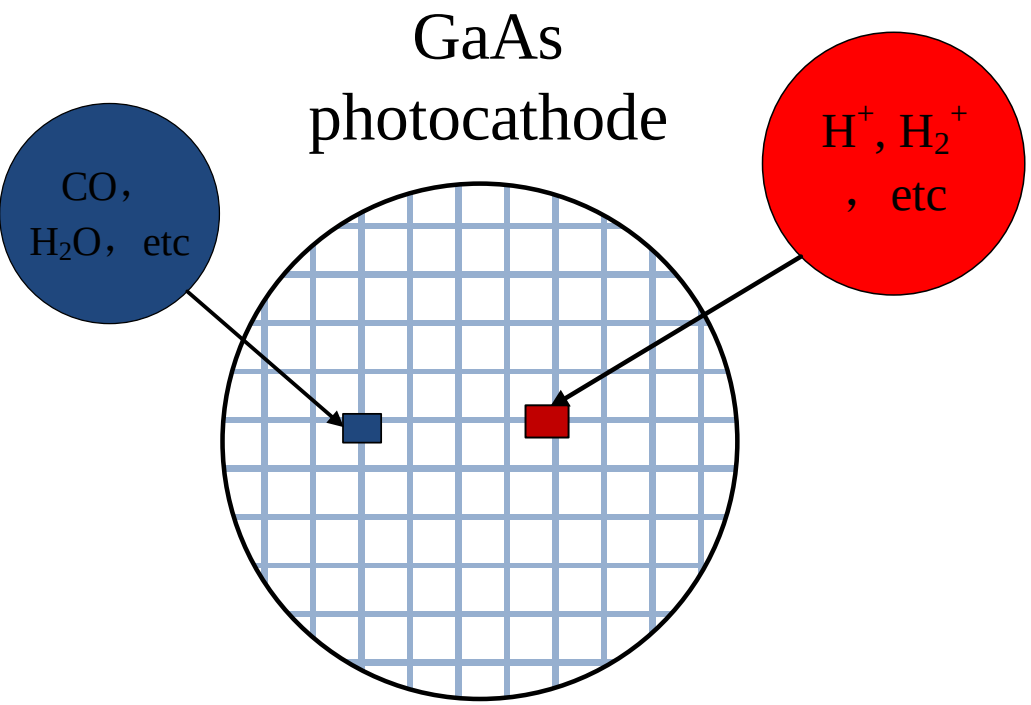

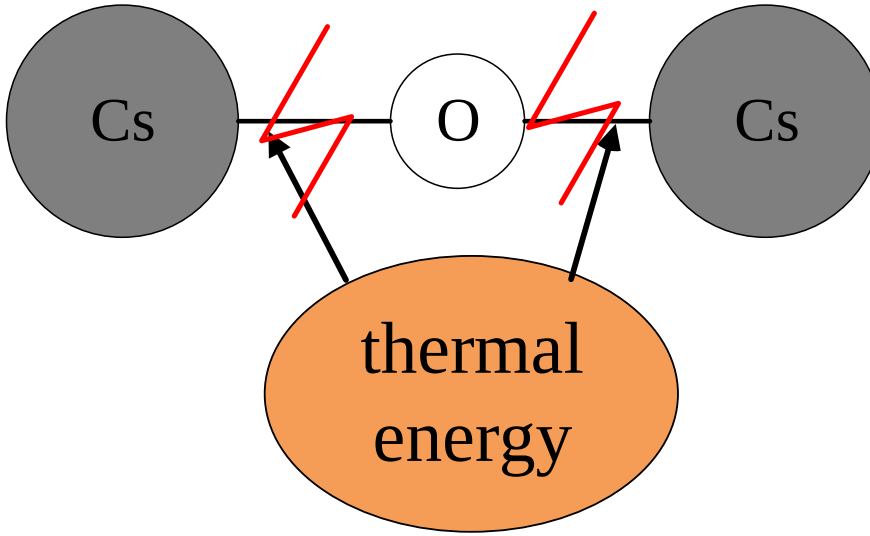

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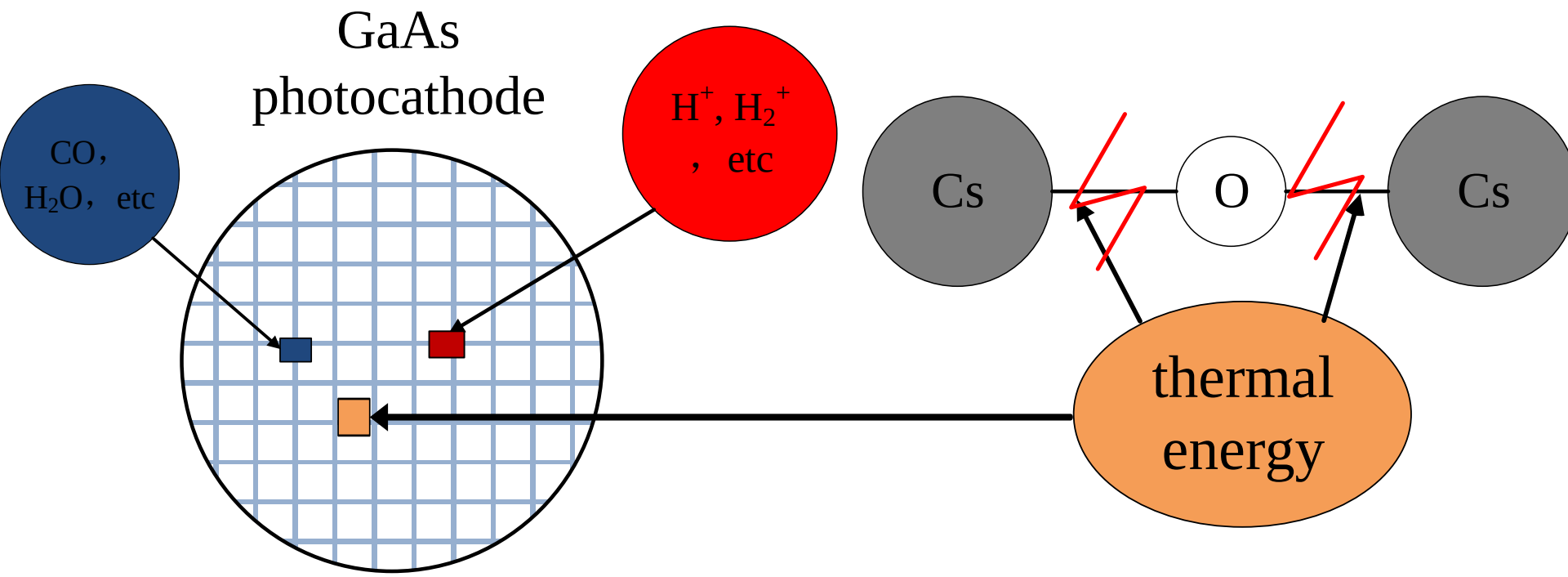
Physical process



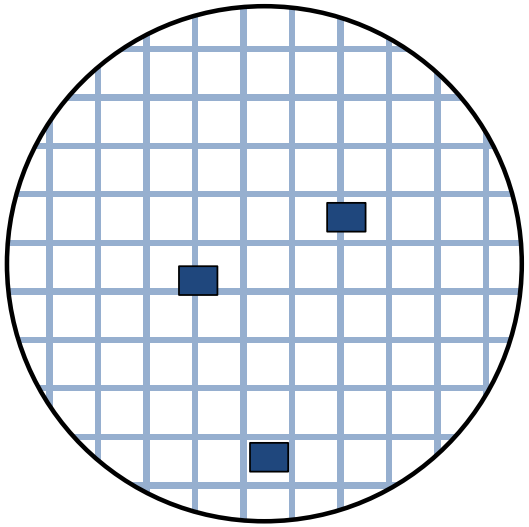
Number of activated regions: m

Ratio: $\theta(t)$

$$\theta(0) = 1, \eta(t) = \eta_0\theta(t)$$

$$I(t) = I_0\theta(t)$$

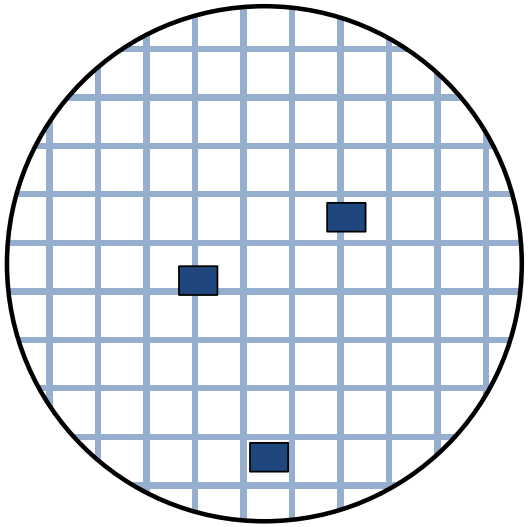
2.1 Vacuum



p: pressure;
kp: collision times;
A: the probability of inactivation

Calabrese R, et al. Rev. Sci. Ins., 1994, 65(2): 343-348
Calabrese R, et al. APL, 1994, 65(3): 301-302

2.1 Vacuum



$$\frac{d\theta}{dt} = -\frac{Akp}{m}\theta$$

$$I(t) = I_0 \exp\left(-\frac{Akpt}{m}\right)$$

$$\tau_p = m/(Akp)$$

p: pressure;

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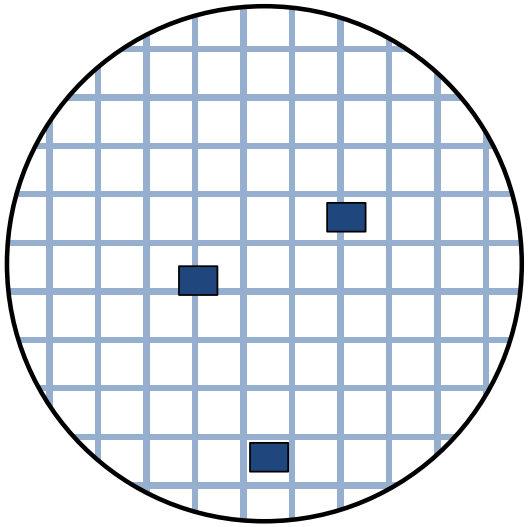

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p: pressure;
kp: collision times;
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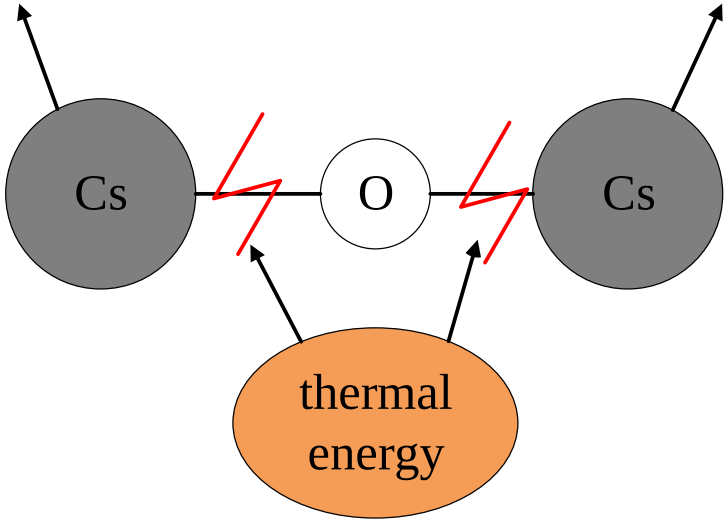
Life-time is inversely proportional to pressure

Calabrese R, et al. Rev. Sci. Ins., 1994, 65(2): 343-348
Calabrese R, et al. APL, 1994, 65(3): 301-302

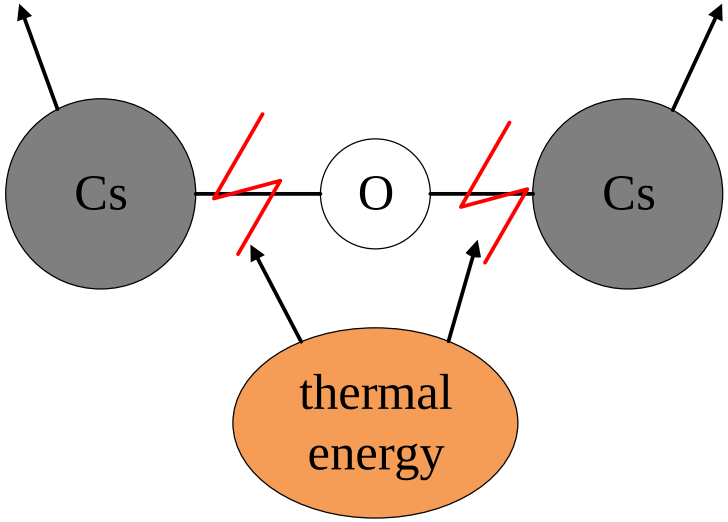
2.2 Temperature



Temperature Programmed Desorption (TPD) process，Polanyi-Wigner formula：

Iijima,IPAC'10, 2323-2325;
Kuriki M, et al. NIMA. 2011, 637(S1):87-90

2.2 Temperature



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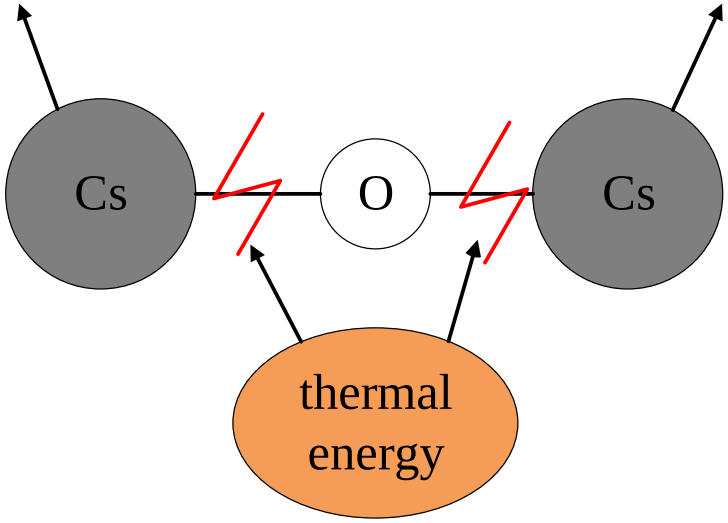

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$$k_n = \nu_n \exp\left(-\frac{E_a}{RT}\right)$$

$$\eta = \eta_0 \theta$$

$$\frac{\mathrm{d}\eta}{\mathrm{dt}} = -\eta_0^{1-n} k_n \eta^n$$

$$\eta_T(t) = \eta_0 [1 - (1-n) k_n t]^{\frac{1}{1-n}}$$

$$\tau_T = \left(\frac{e^{n-1} - 1}{n-1}\right) \nu_n^{-1} \exp\left(\frac{E_a}{RT}\right)$$

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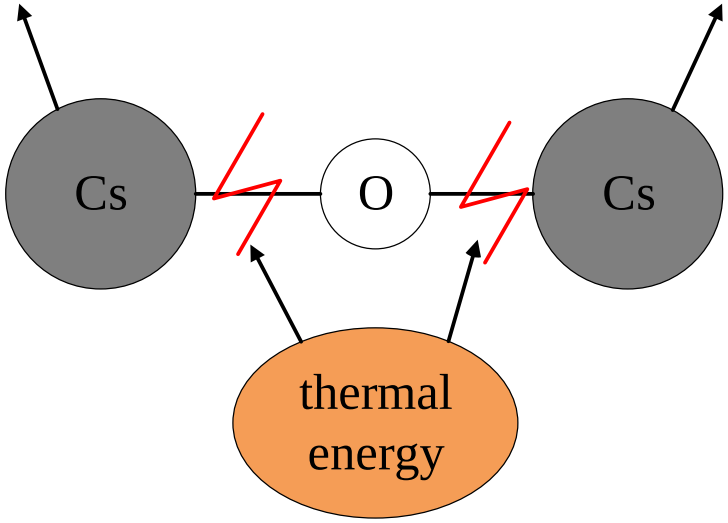

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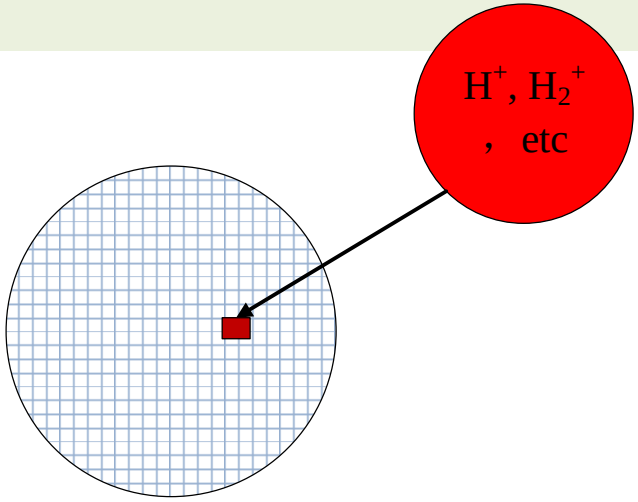
Life-time reduces exponentially

Iijima,IPAC'10, 2323-2325;
Kuriki M, et al. NIMA. 2011, 637(S1):87-90

2.3 Ion back-bombardment

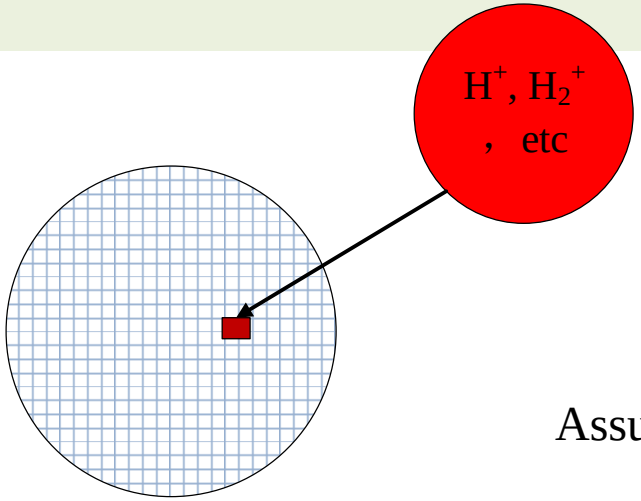


$\beta_0 pI$: the positive ion generation rate

i: the probability that one ion inactivating one region

P: laser power

2.3 Ion back-bombardment



$$\frac{d\theta}{dt} = -\frac{i\beta_0 pI\theta}{m} \qquad I(t) = \frac{e}{h\nu_0}\eta(t)P = \frac{e}{h\nu_0}rP\theta(t)$$

Assuming $\kappa = eri\beta_0 pP/(h\nu_0)$ then $\frac{d\theta}{dt} = -\frac{\kappa\theta^2}{m}$

$$\theta(t) = \frac{1}{1+\kappa t/m} \qquad \eta_B(t) = \frac{\eta_0}{1+\kappa t/m}$$

$$\tau_B = \frac{m}{\kappa}(e-1)$$

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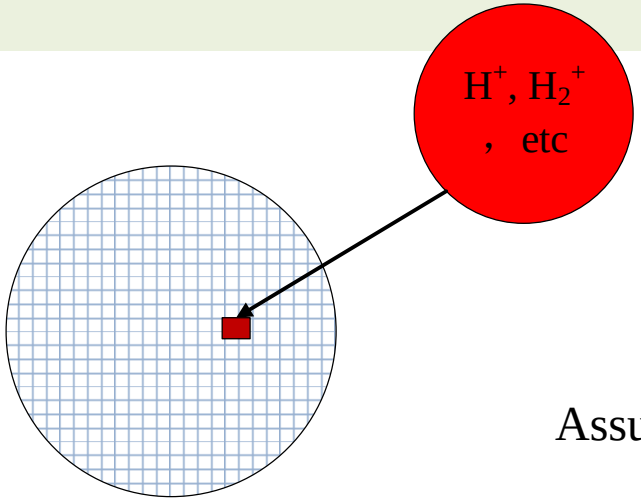

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$\beta_0 pI$: the positive ion generation rate
i: the probability that one ion inactivating one region
P: laser power

Life-time is inversely proportional to pP

2.4 The operation life-time

$$\eta(t) = \frac{\eta_0[1-(1-n)k_n t]^{\frac{1}{1-n}}}{1+\kappa t/m}\exp\left(-\frac{Akpt}{m}\right) \Rightarrow \frac{1}{\tau} = \frac{1}{\tau_P} + \frac{1}{\tau_T} + \frac{1}{\tau_B}$$

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$$\ln\eta(t) = \ln\eta_0 - \frac{Akpt}{m} - \frac{1}{n-1}\ln[1+(n-1)k_n t] - \ln(1+\kappa t/m)$$

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Vacuum

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Vacuum

Temperature

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Vacuum

Temperature

Ion back bombardment

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Vacuum

Temperature

Ion back bombardment

The main equation demonstrates that in **logarithmic coordinate**:

2.4 The operation life-time

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Vacuum | Temperature | Ion back bombardment

The main equation demonstrates that in **logarithmic coordinate**:

Current decays straight: Vacuum;

A logarithmic curve: Temperature or Ions.

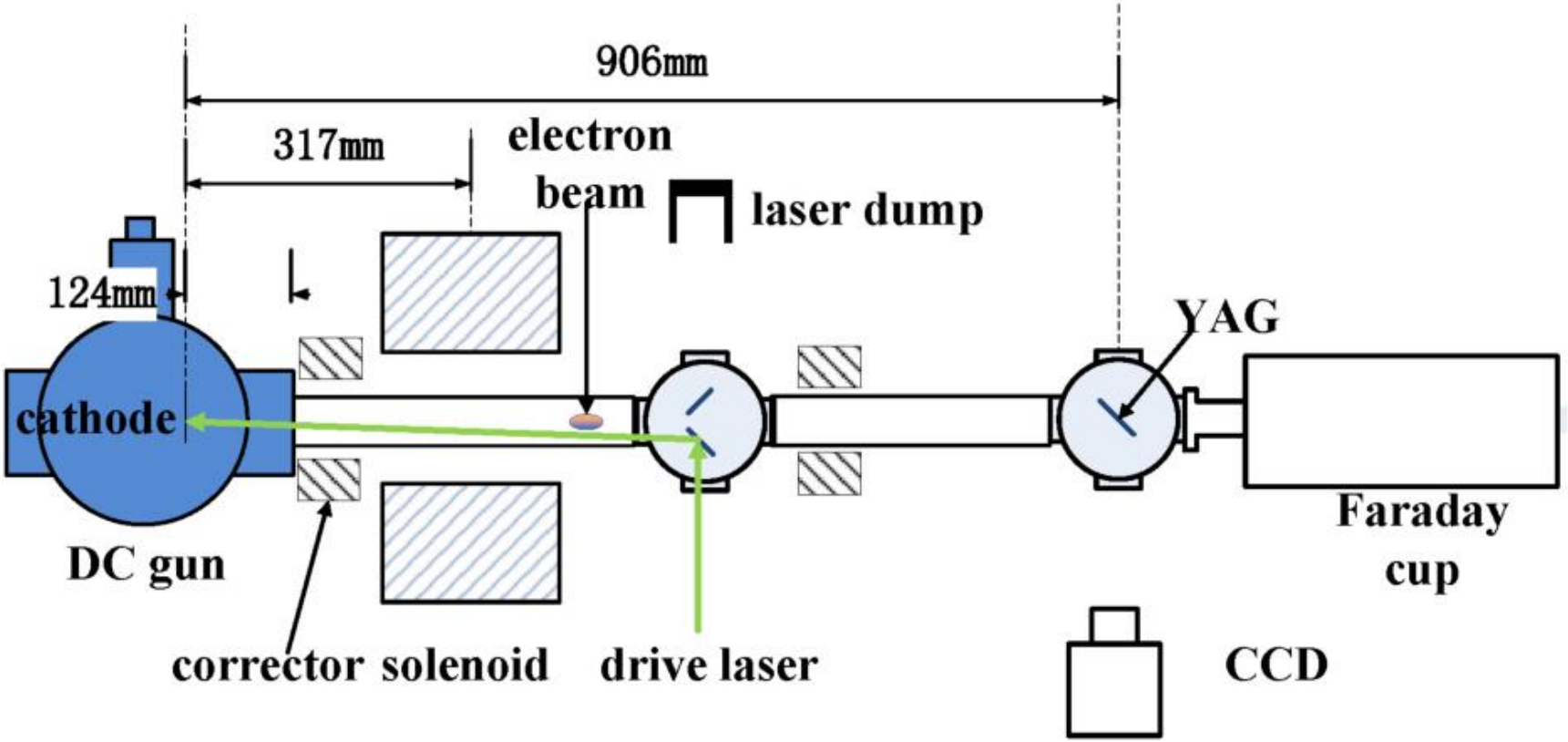
Outline

- 1. Background Introduction
- 2. Physical Model
- 3. Experiment Progress
- 4. Summary
- 5. Further studies

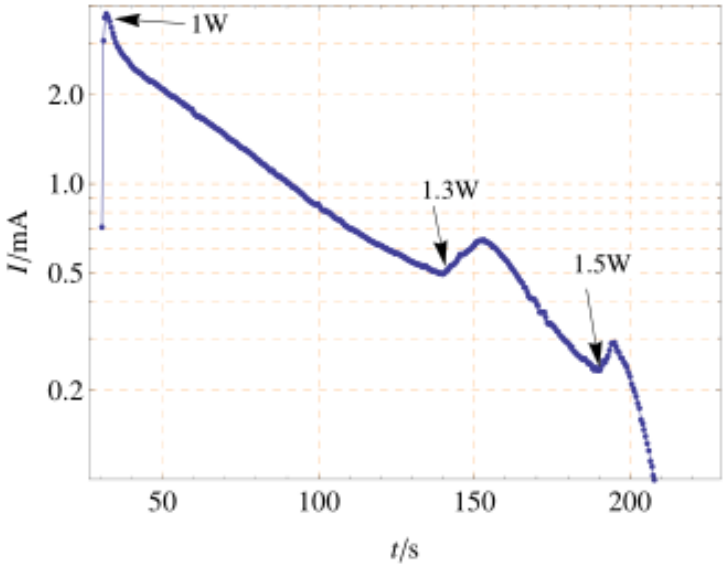
3 Experiment progress

- 3.1 Initial Status
- 3.2 Optimization Strategies
  - Vacuum
  - Temperature
- 3.3 Present status (5mA/0.5h)

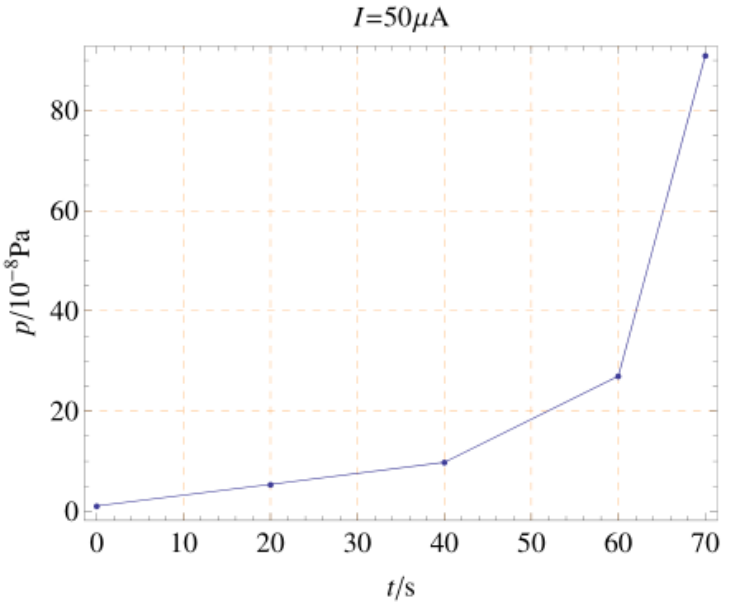
Experiment layout



3.1 Initial status

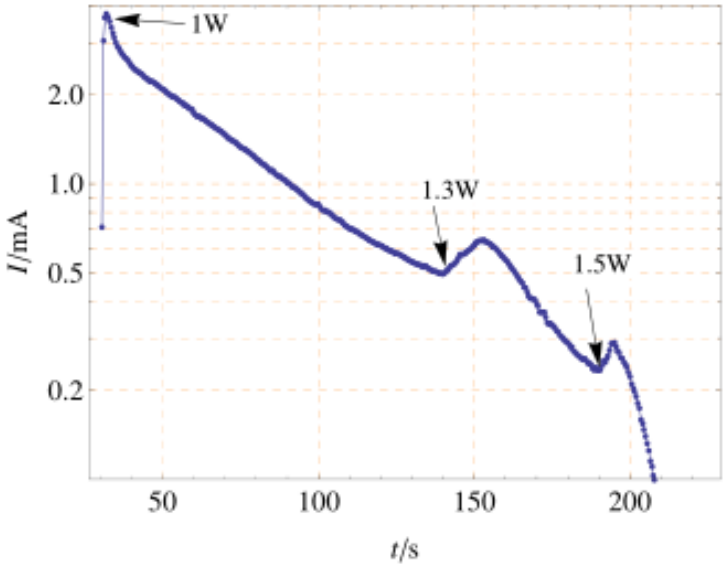


Beam current

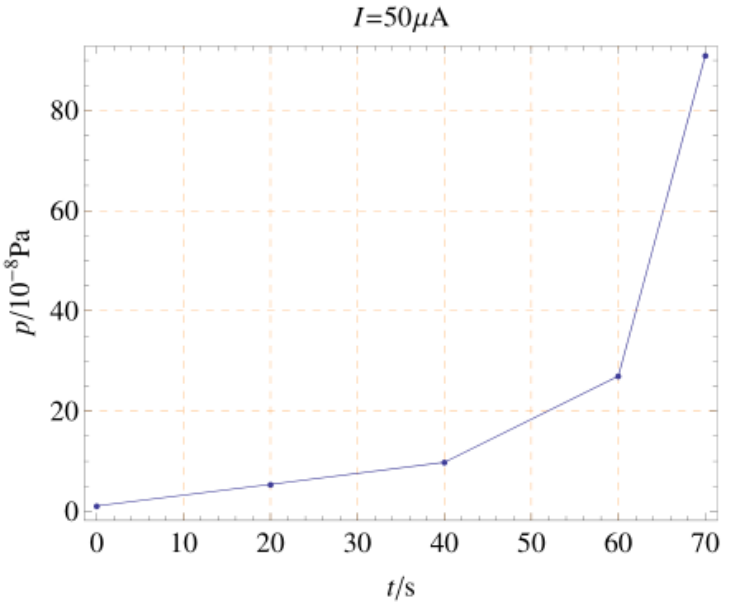


Vacuum in tiny current

3.1 Initial status



Beam current



Vacuum in tiny current

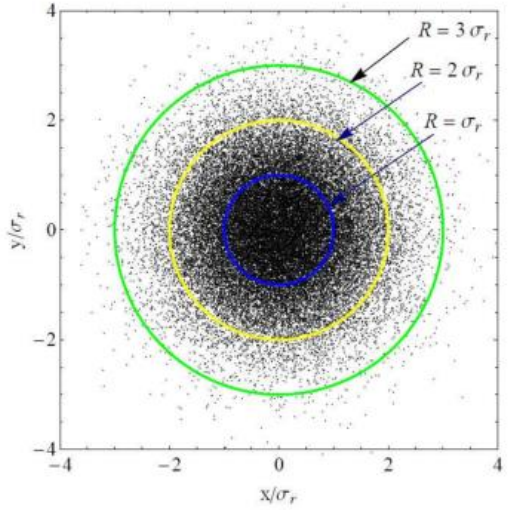
10^{-7}Pa → 1 W → 50s

3.2 Vacuum—①beam losses

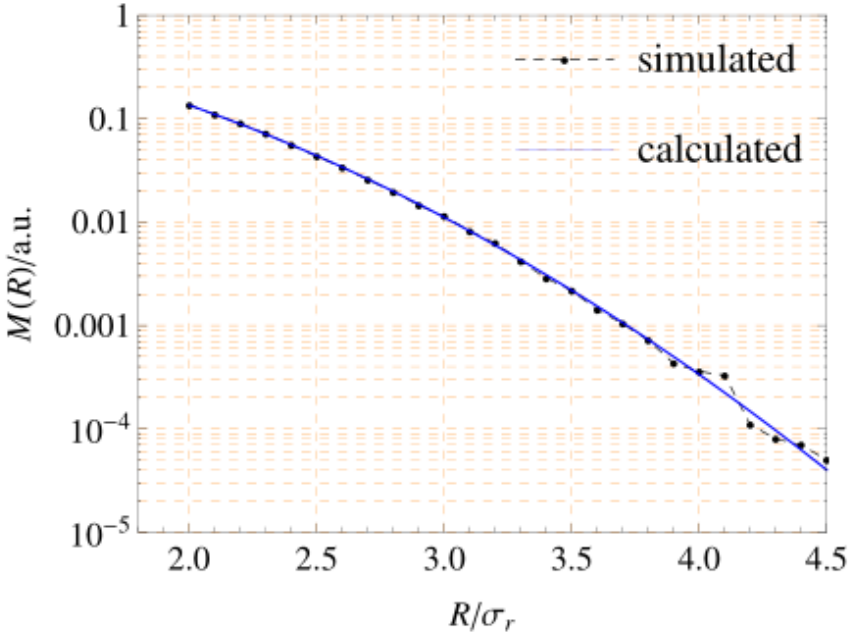
$$f(r,\theta)r\mathrm{d}r\mathrm{d}\theta = \frac{1}{2\pi\sigma_r^2}\exp\left(-\frac{r^2}{2\sigma_r^2}\right)r\mathrm{d}r\mathrm{d}\theta$$

$$F(R) = \int_0^{2\pi}\int_0^R f(r,\theta)r\mathrm{d}r\mathrm{d}\theta = \int_0^R r\exp\left(-\frac{r^2}{2\sigma_r^2}\right)/\sigma_r^2\mathrm{d}r$$

$$M(R) = 1 - F(R) = \exp\left(-\frac{R^2}{2\sigma_r^2}\right)$$



2D Gauss Distribution



Beam losses versus the tube dimension

3.2 Vacuum—①beam losses

$$f(r,\theta)r\mathrm{d}r\mathrm{d}\theta = \frac{1}{2\pi\sigma_r^2}\exp\left(-\frac{r^2}{2\sigma_r^2}\right)r\mathrm{d}r\mathrm{d}\theta$$

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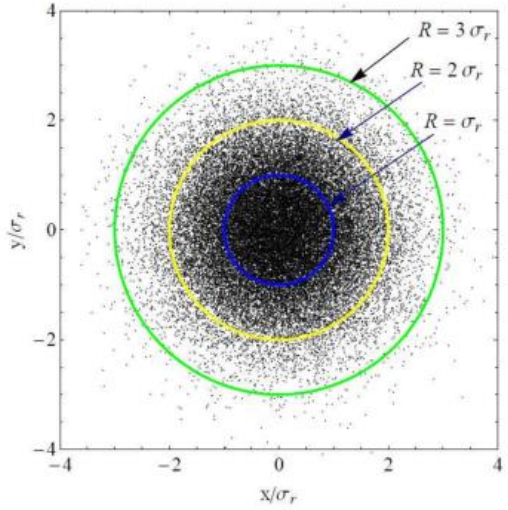
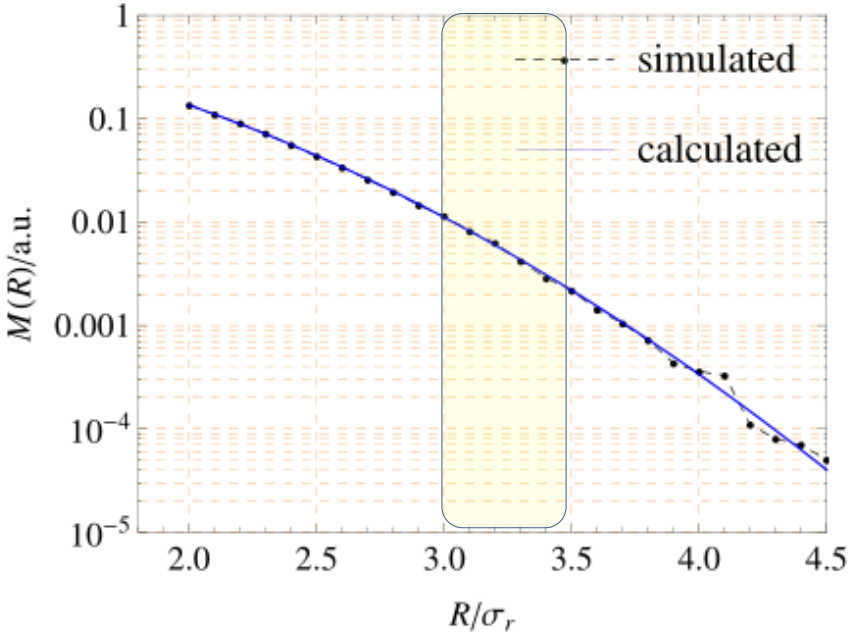
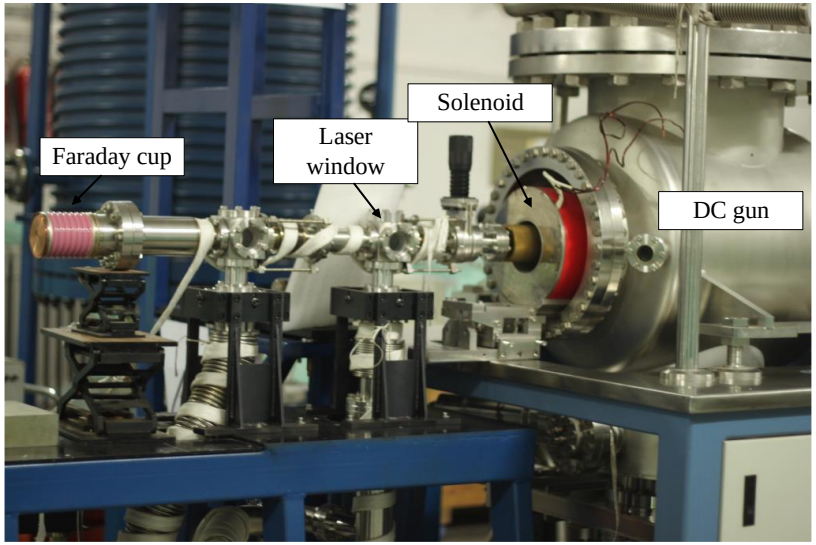


2D Gauss Distribution

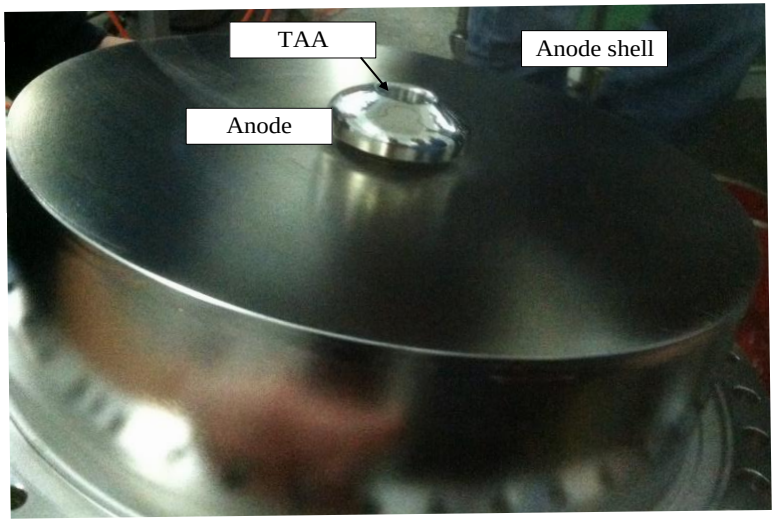


Beam losses versus the tube dimension

3.2 Vacuum—②reasons

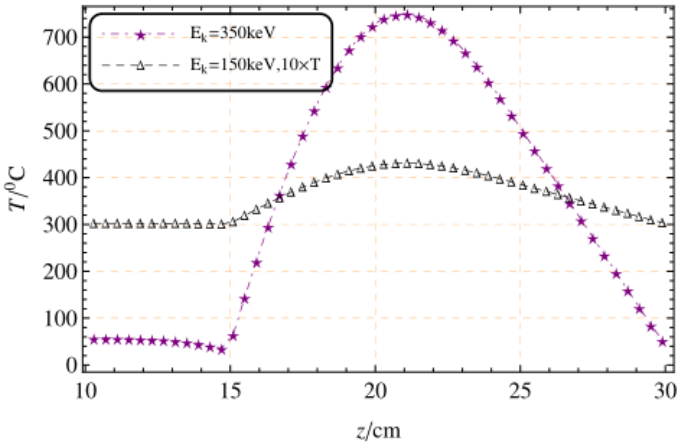


Initial experiment setup



Initial anode shell

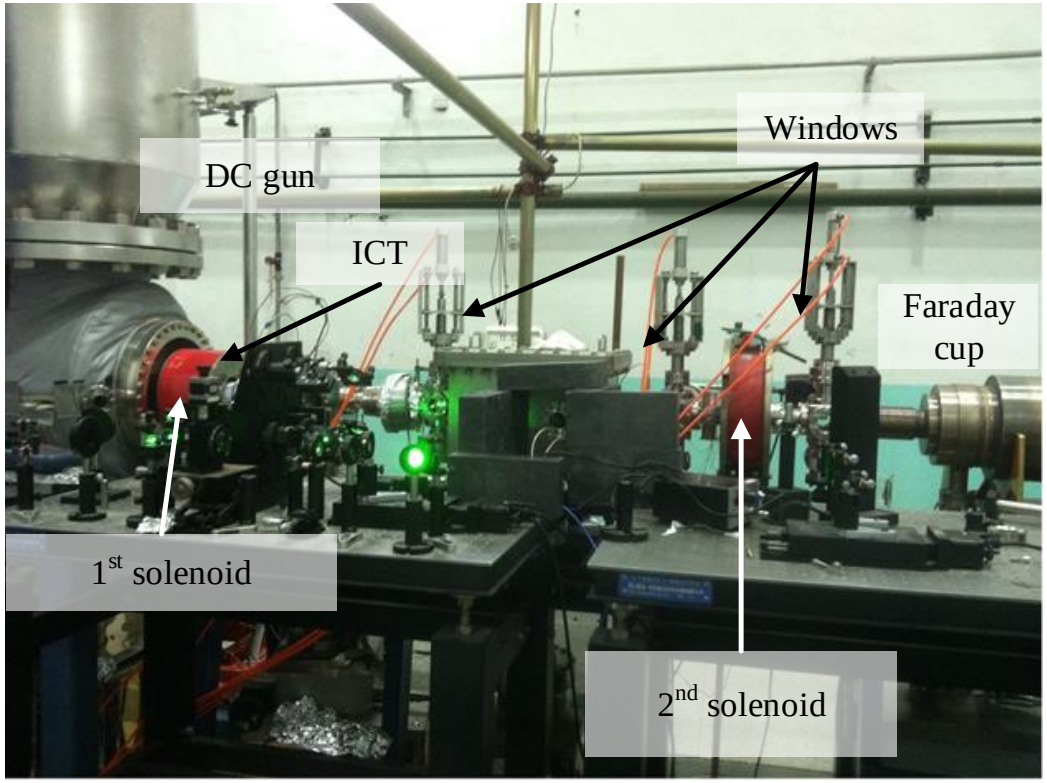
- Anode hole (Φ20mm)
- Tube for anode adjust (TAA，Φ20mm)
- Large loss around cathode



Temperature along TAA

D Wu, et al. High Power Laser and Particle Beams, 2014, 26(01):2615102

3.2 Vacuum—③strategies



The improved beam line setup

Strategies：

1. Anode hole: Φ50mm

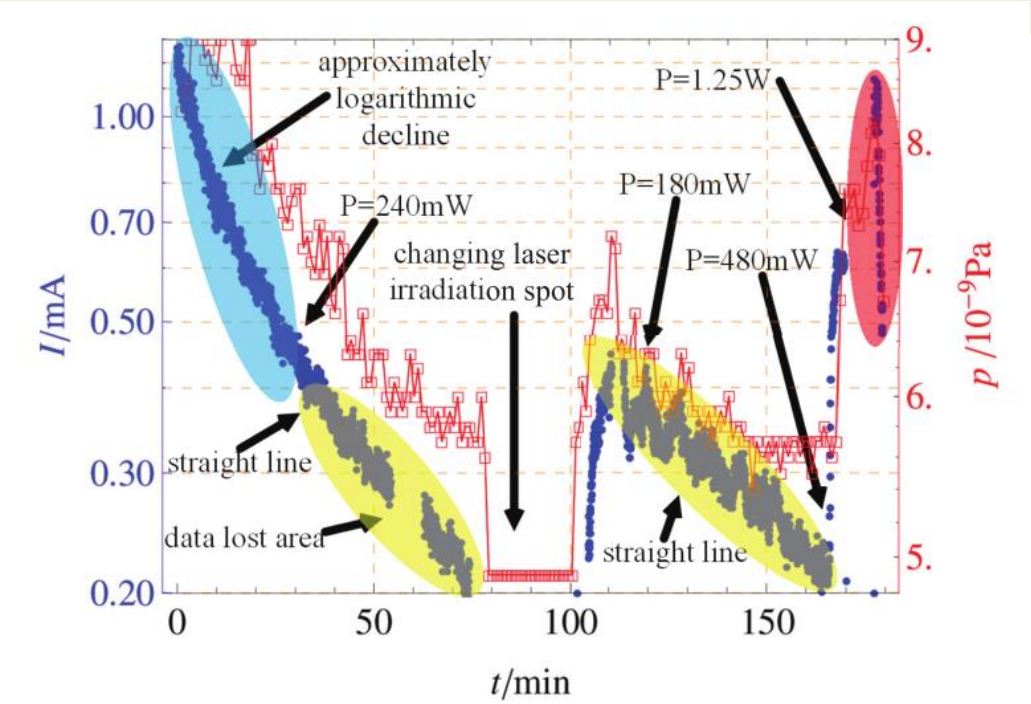
2. Cancer TAA， the drift tube: Φ63mm

3. Newly designed Faraday cup, far away (2m)

4. More pumps

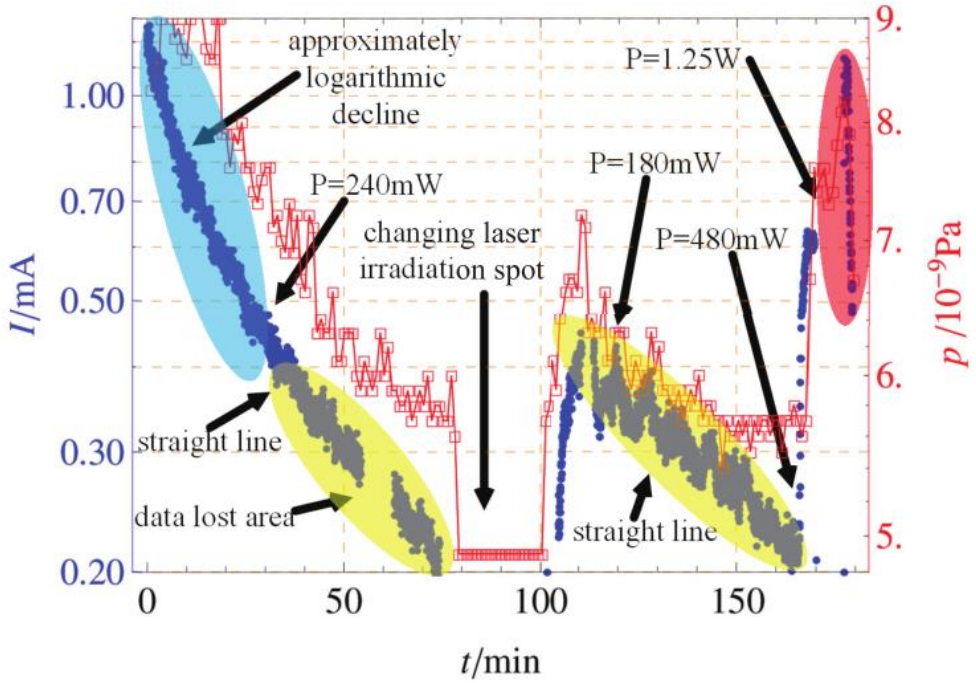
6. More magnetic correctors

3.2 Vacuum—④optimization result



Current and pressure after vacuum condition improved

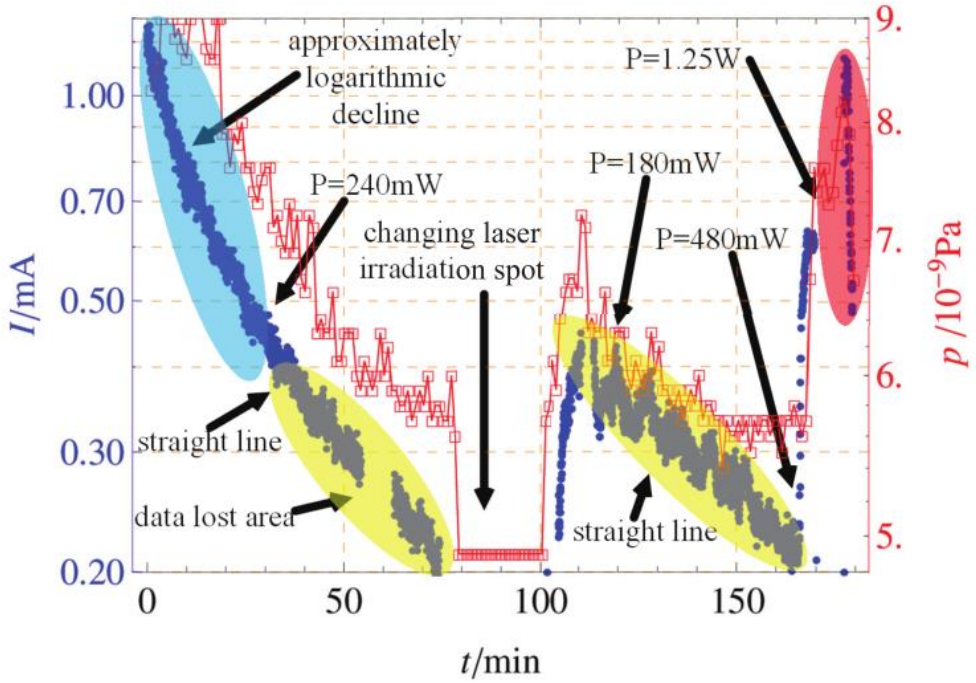
3.2 Vacuum—④optimization result



Current and pressure after vacuum condition improved

Life time~1h

3.2 Vacuum—④optimization result

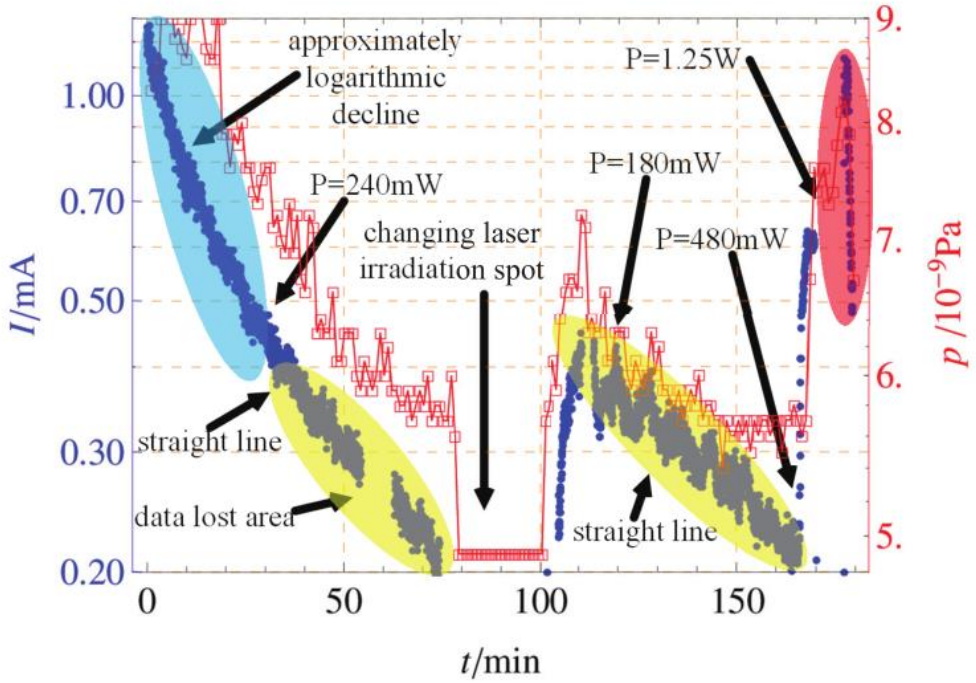


Current and pressure after vacuum condition improved

Life time~1h

Blue area---ion back-bombardment

3.2 Vacuum—④optimization result



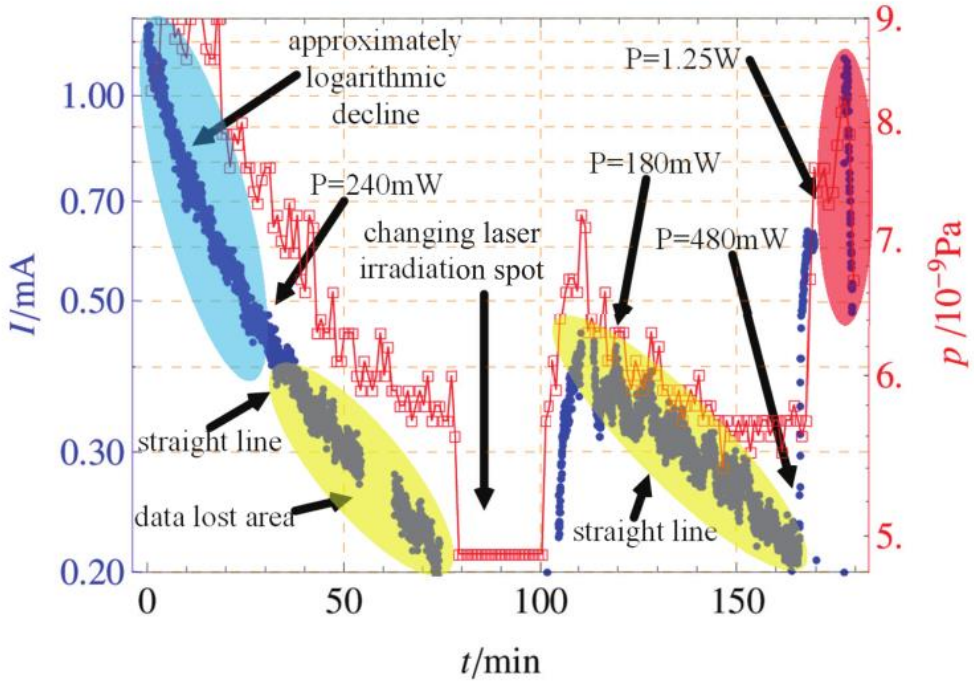
Current and pressure after vacuum condition improved

Life time~1h

Blue area---ion back-bombardment

Red area---temperature

3.2 Vacuum—④optimization result



Current and pressure after vacuum condition improved

Life time~1h

Blue area---ion back-bombardment

Red area---temperature

The new limit

temperature

3.3 Thermal effects—①experiment setup

$$T = \frac{Q_0 A}{I_0} \ln\left(\frac{P_{\max}\lambda_l \eta_0}{1.24 I_0}\right)$$

$$Q_0 A = I_{max}\tau \frac{e-1}{e}$$

P_{max}=?

3.3 Thermal effects—①experiment setup

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In the experiment， 600mW

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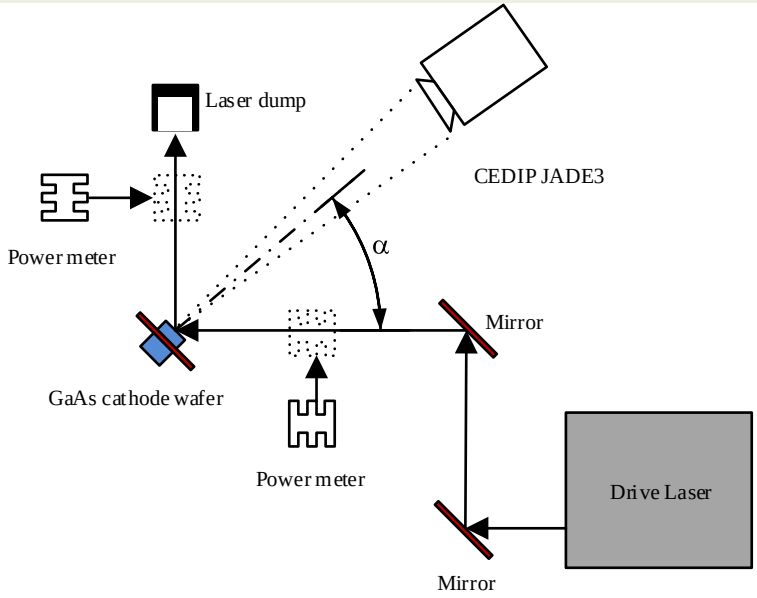

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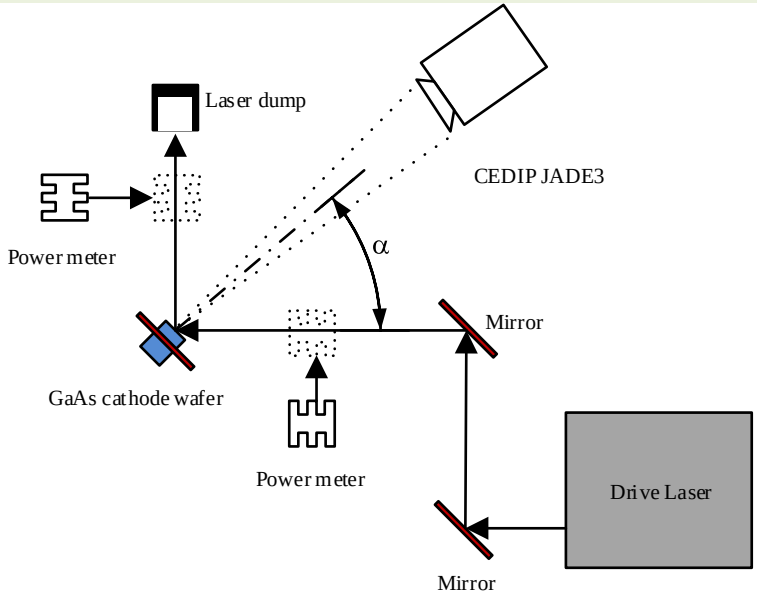
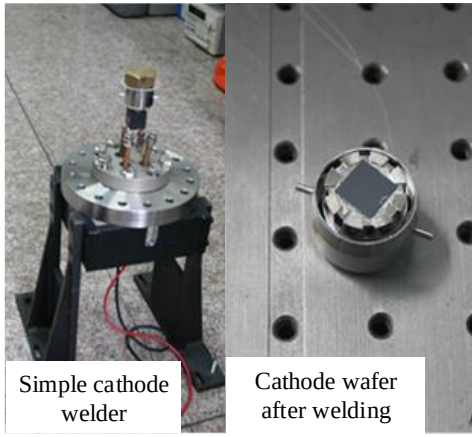
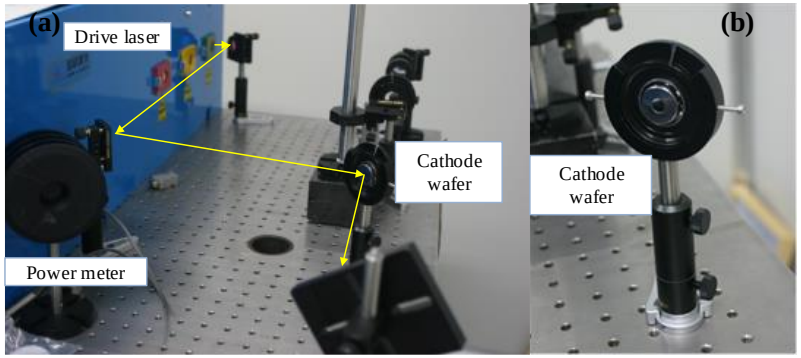


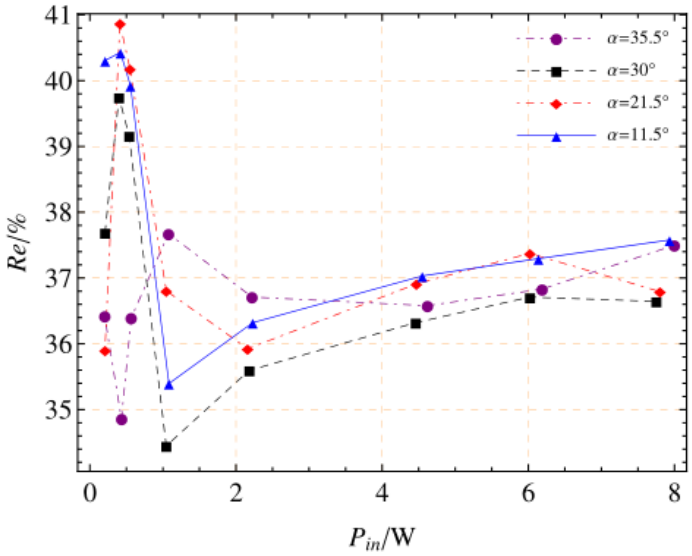


Simple cathode welder

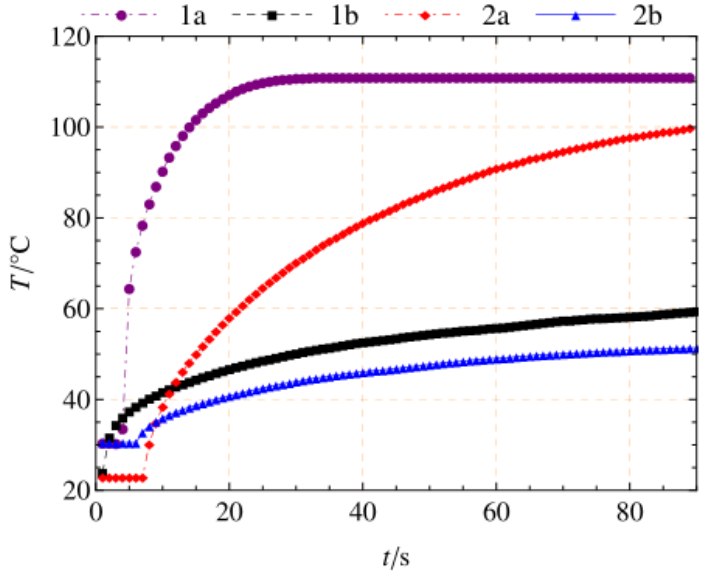


Experiment setup

3.3 Thermal effects—②welding



Reflectivity



Thermal equilibrium

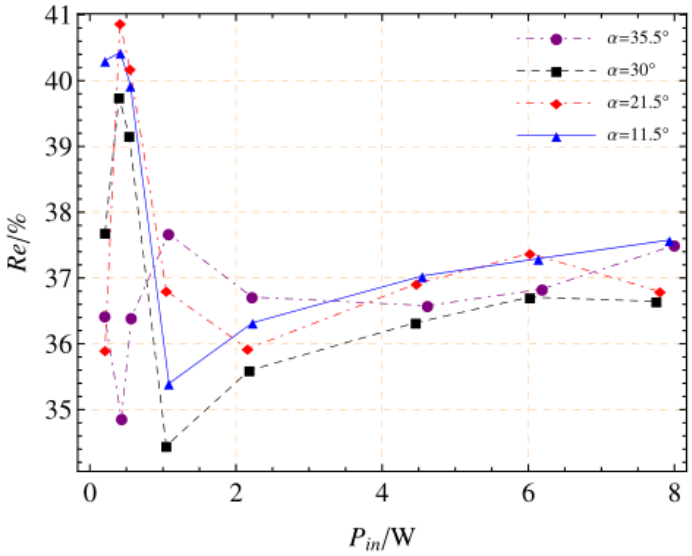
Tab. Experiment parameters

Experimental group	P_a/W	Control group	P_a/W
1a, non-indium	5.29	1b, indium welding	5.08
2a, non-indium	1.36	2b, indium welding	1.41

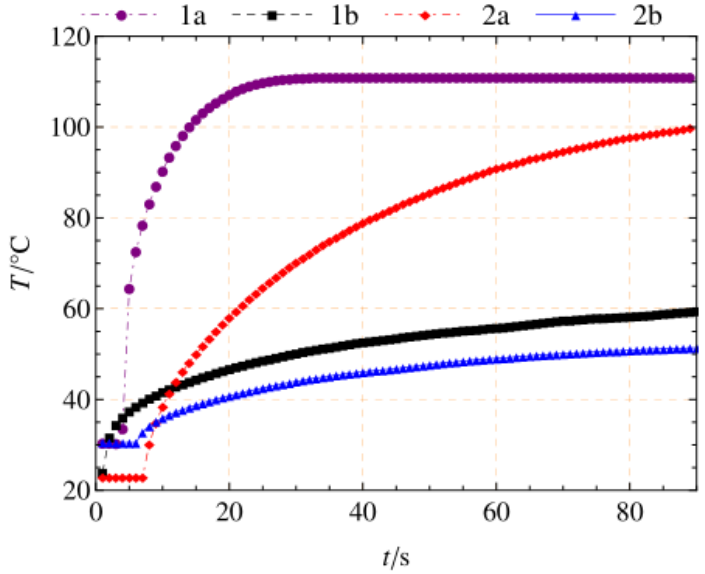
Tab. Temperature rise

Group number	1a	1b	2a	2b
Thermal equilibrium time/s	30	205	135	780
Equilibrium temperature/°C	110.6	110.3	68.6	70.5

3.3 Thermal effects—②welding



Reflectivity



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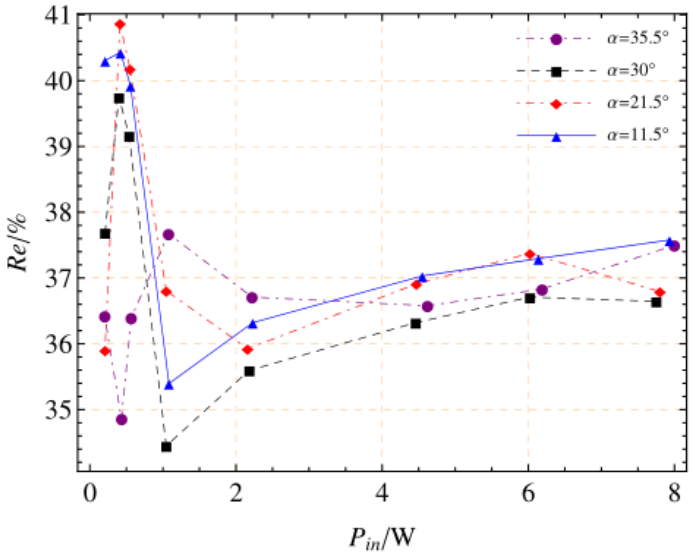

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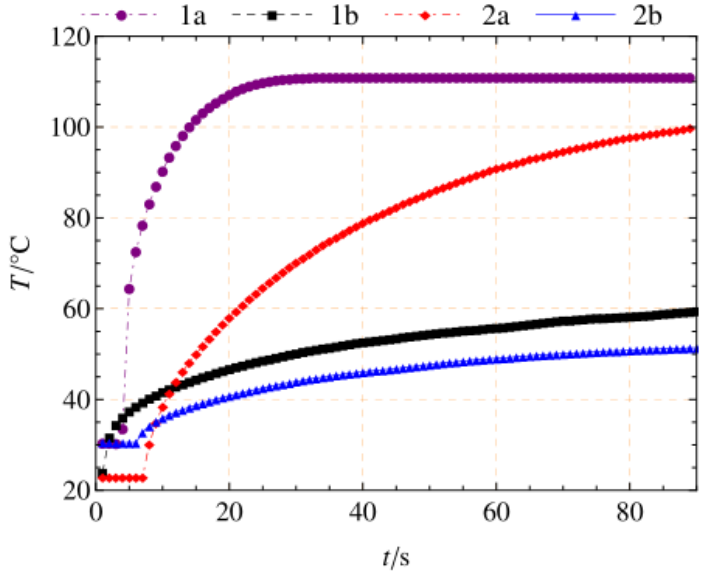

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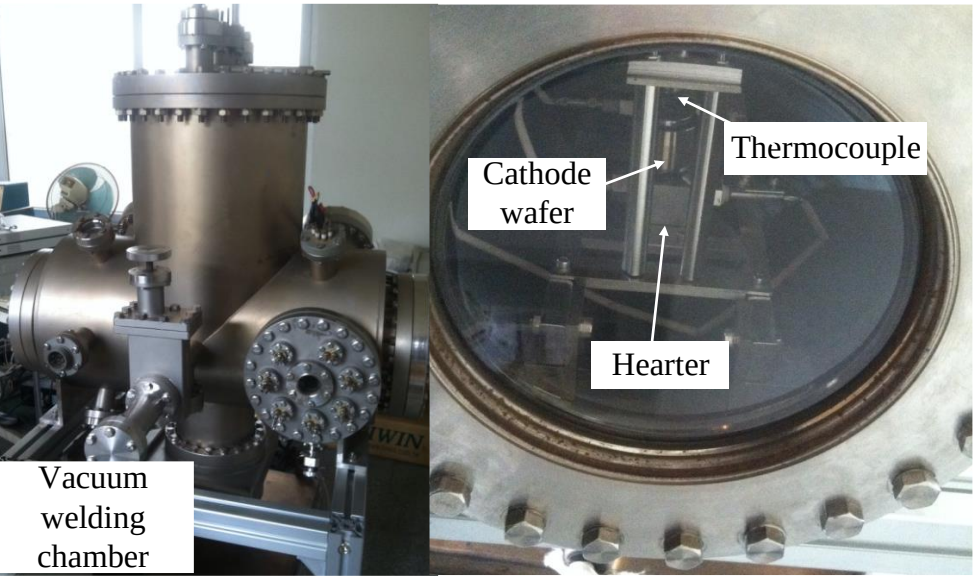
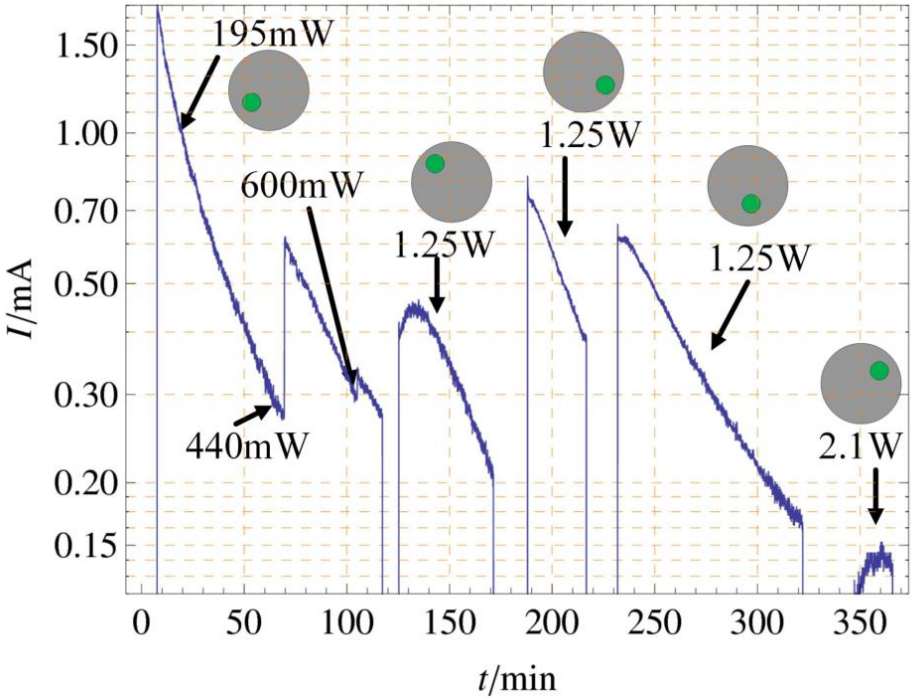
Equilibrium temperature/°C	110.6	110.3	68.6	70.5

Indium welding slows temperature rise.

3.3 Thermal effects—③improved results

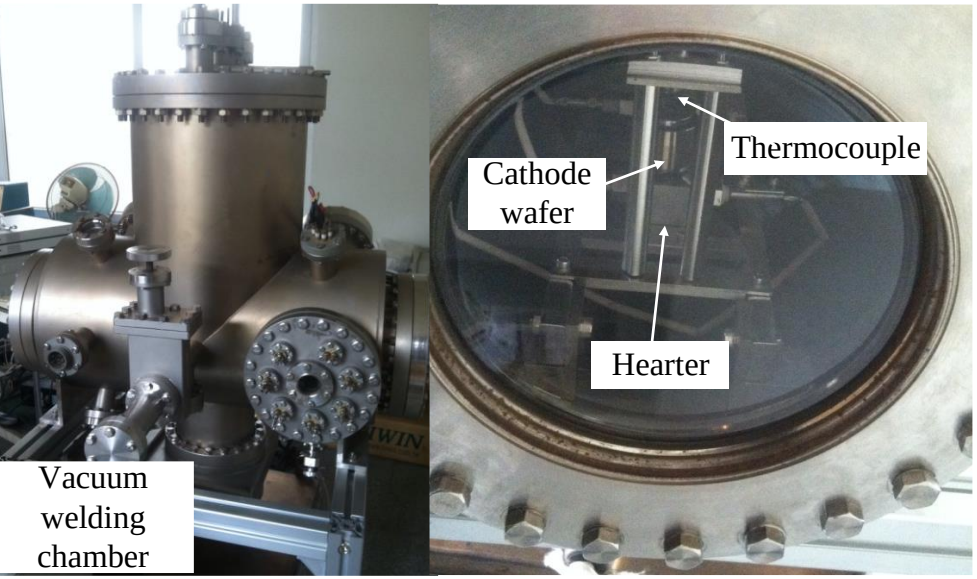


Vacuum welding chamber



Current output after temperature reduced

3.3 Thermal effects—③improved results



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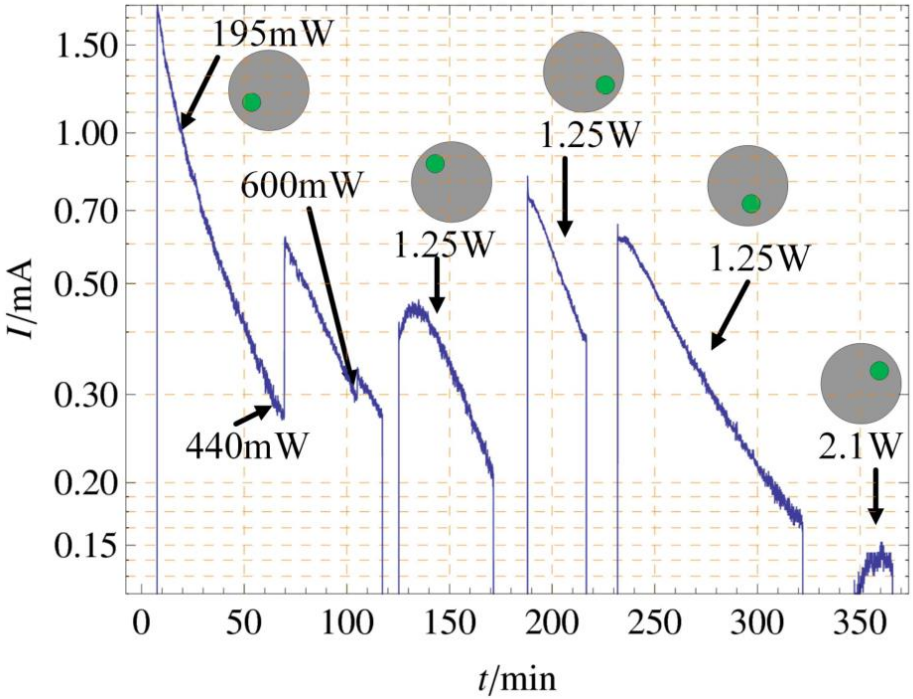
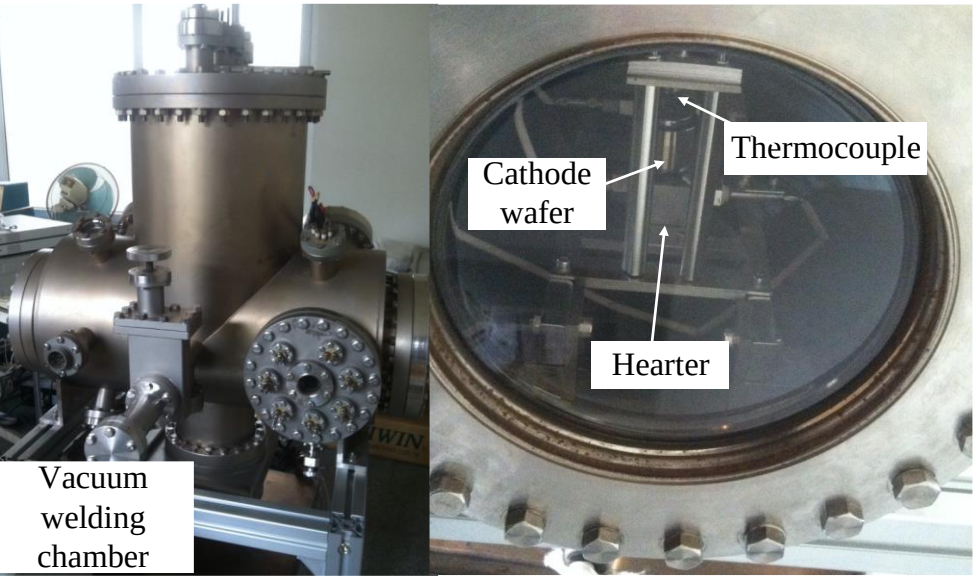


Current output after temperature reduced

- Vacuum, better than 5×10^{-9}Pa

3.3 Thermal effects—③improved results



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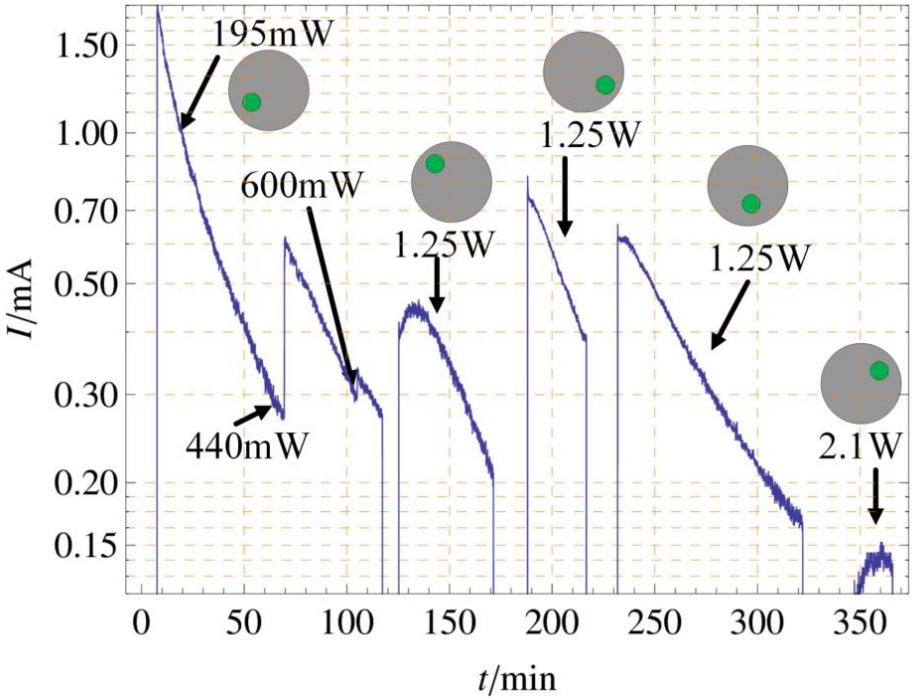
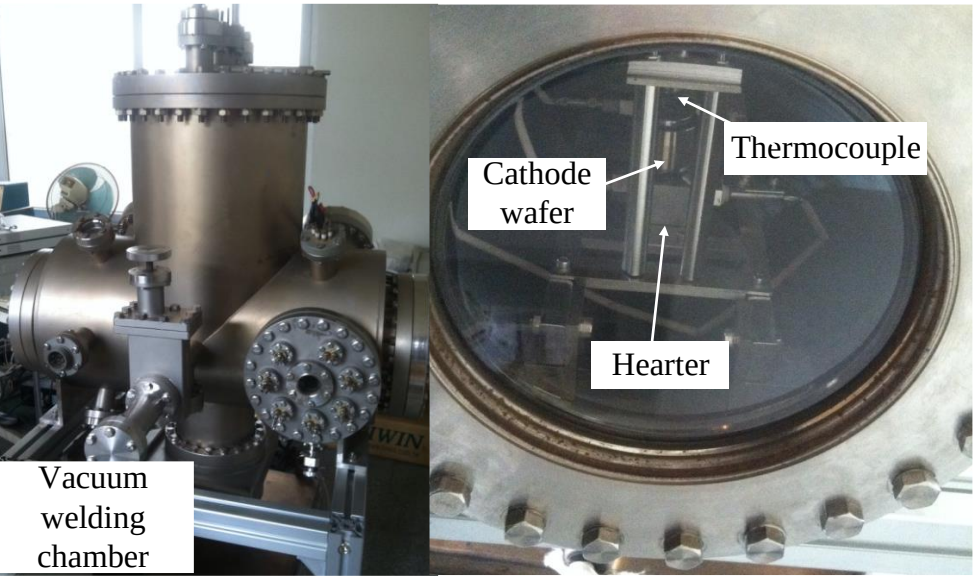


Current output after temperature reduced

- Vacuum, better than 5×10^{-9}Pa
- P>1.25W， life-time>1h

3.3 Thermal effects—③improved results



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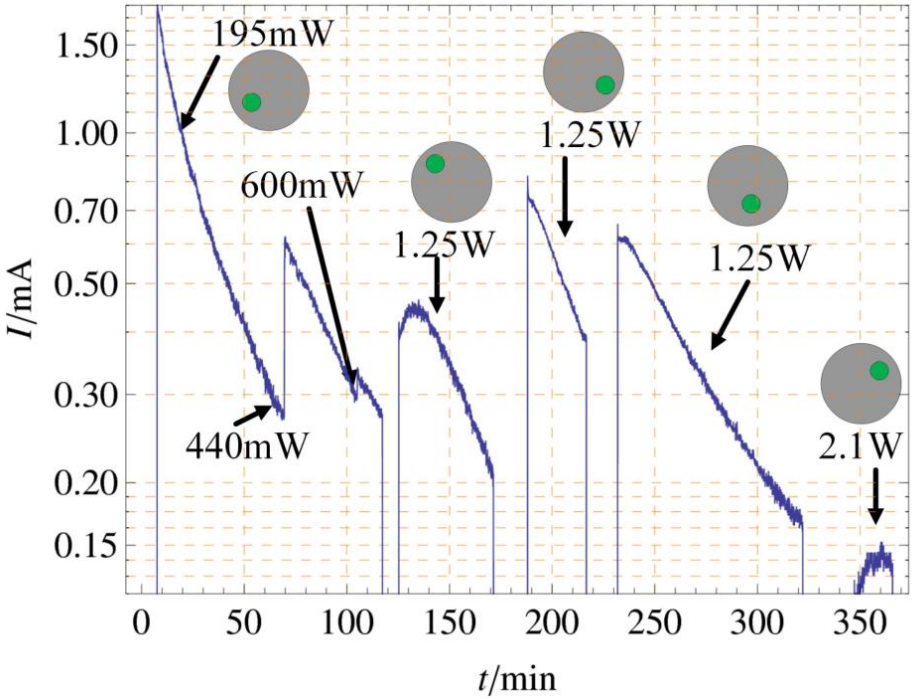
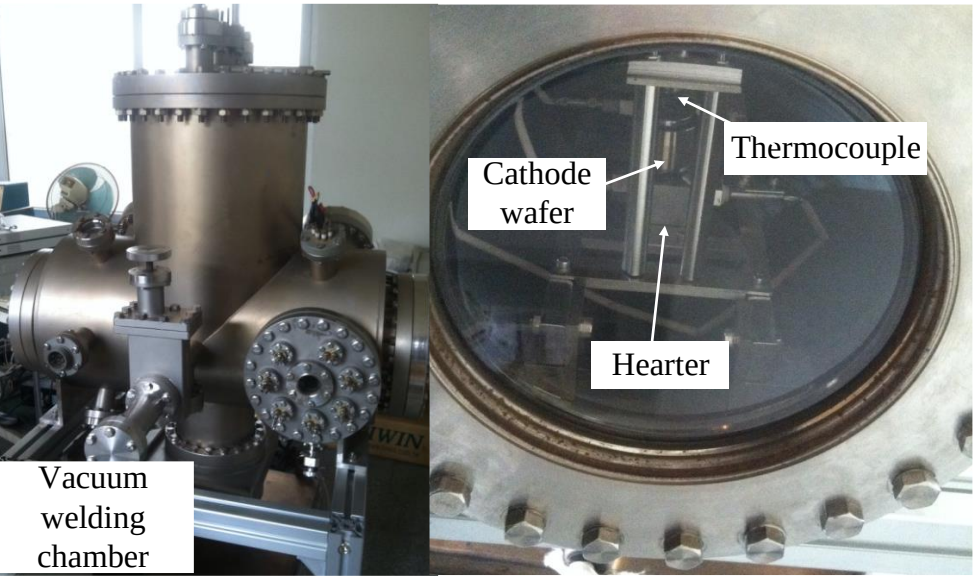


Current output after temperature reduced

- Vacuum, better than 5×10^{-9}Pa
- P>1.25W， life-time>1h
- Approximately the same slope

3.3 Thermal effects—③improved results



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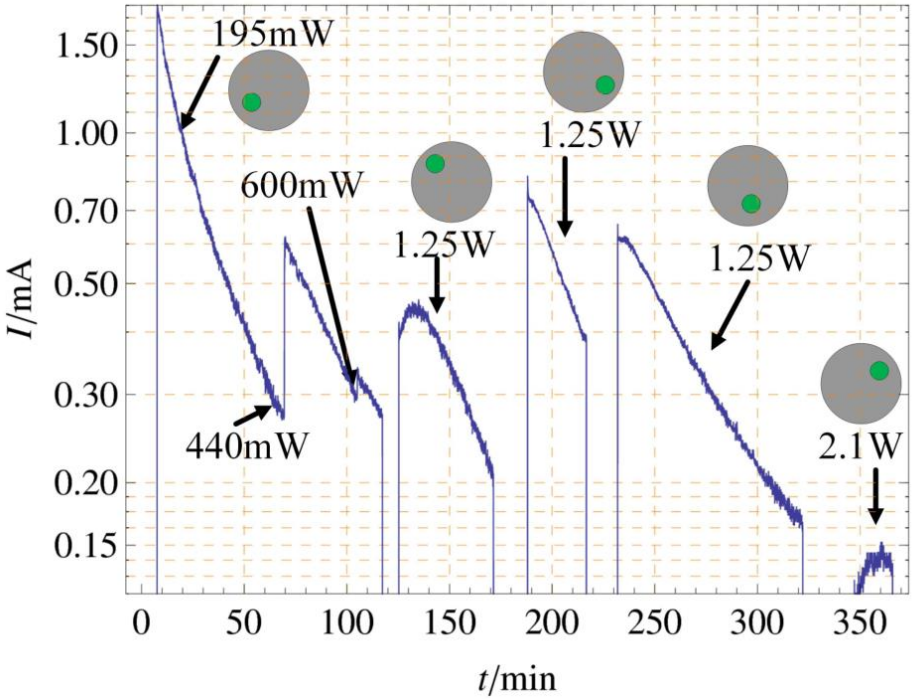


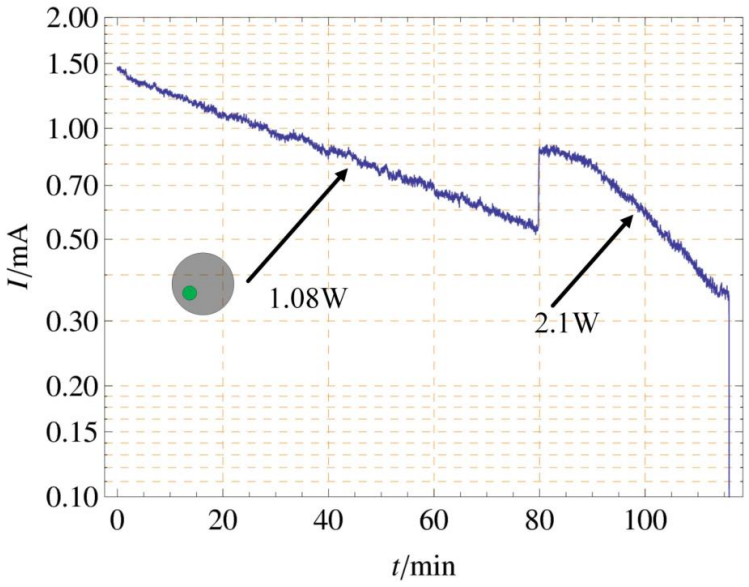
Current output after temperature reduced

- Vacuum, better than 5×10^{-9}Pa
- P>1.25W， life-time>1h
- Approximately the same slope

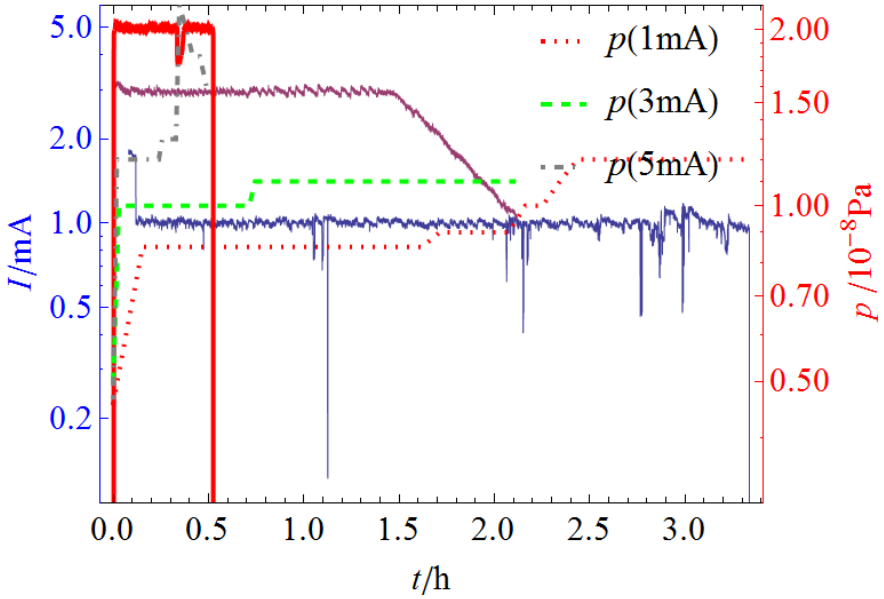
→ The main factor

→ **Vacuum**

3.4 Present status



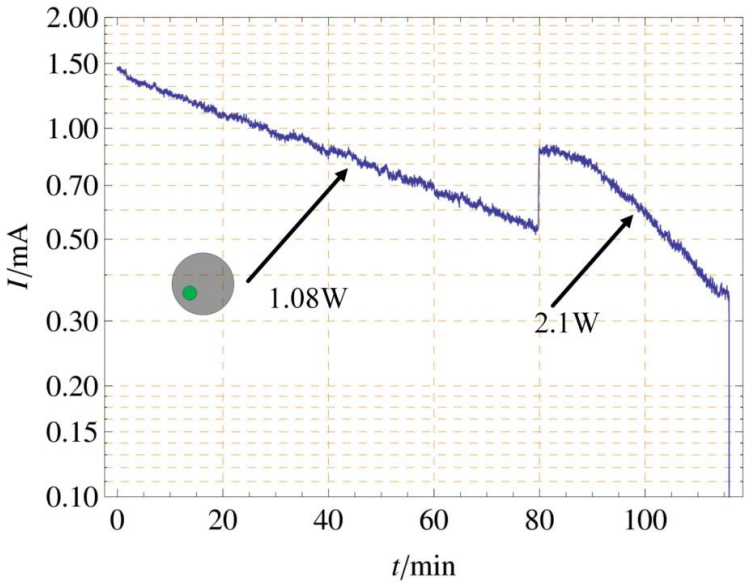
The longest life-time observed



Present status

D Wu, PHD thesis, 2014, Beijing： Tsinghua University

3.4 Present status



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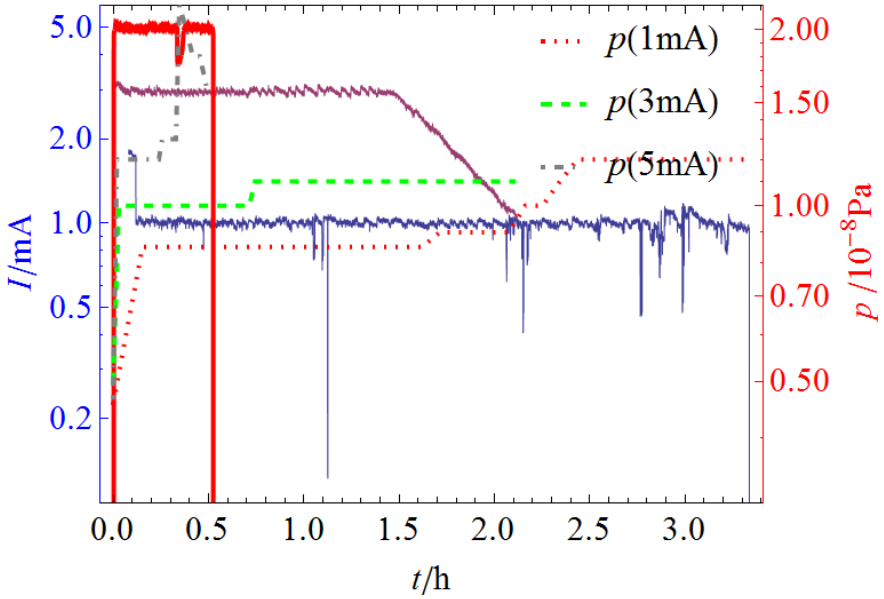

Present status

1.08W， life-time 80min， Q_0A>4.55C

1mA/3.3h、 3mA/1.4h or 5mA/32min

More than 18.7C

D Wu, PHD thesis, 2014, Beijing： Tsinghua University

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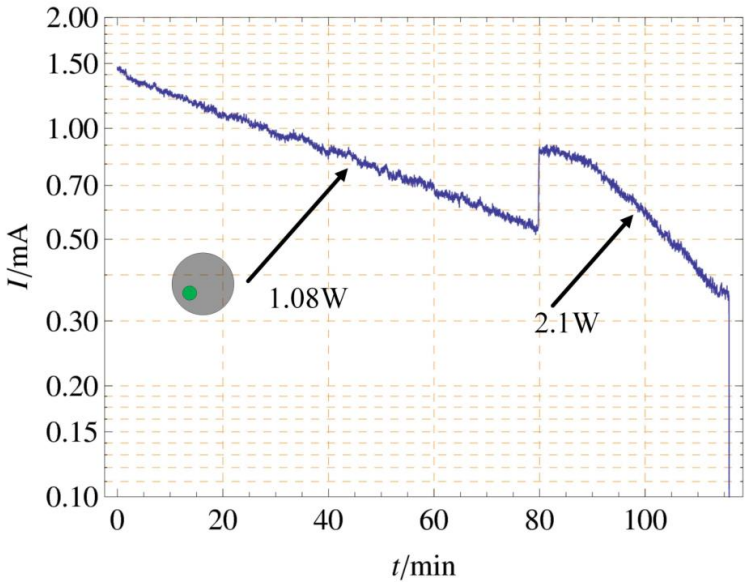

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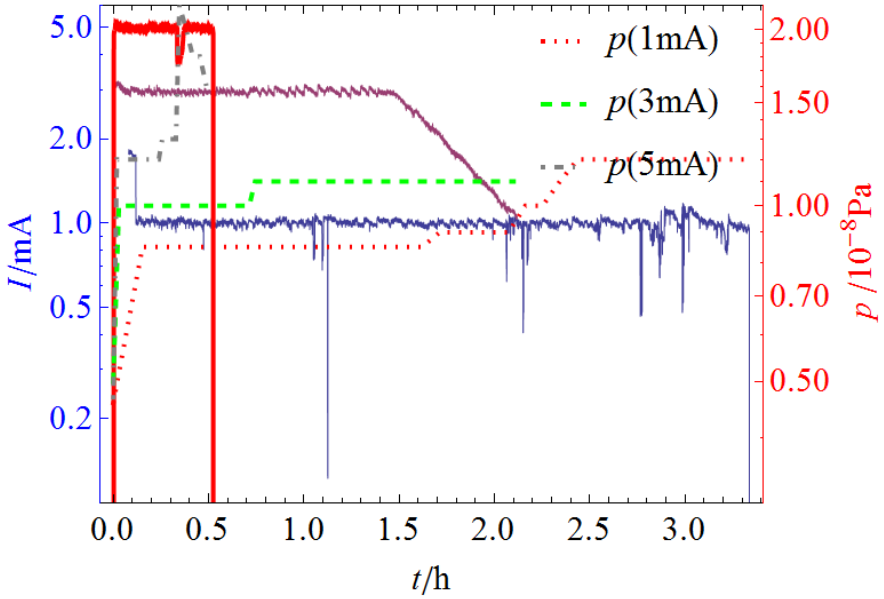


Present status

1.08W， life-time 80min， Q_0A>4.55C

1mA/3.3h、 3mA/1.4h or 5mA/32min

More than 18.7C

First 5mA in China

Consistent with the model

The main factor: vacuum again

D Wu, PHD thesis, 2014, Beijing： Tsinghua University

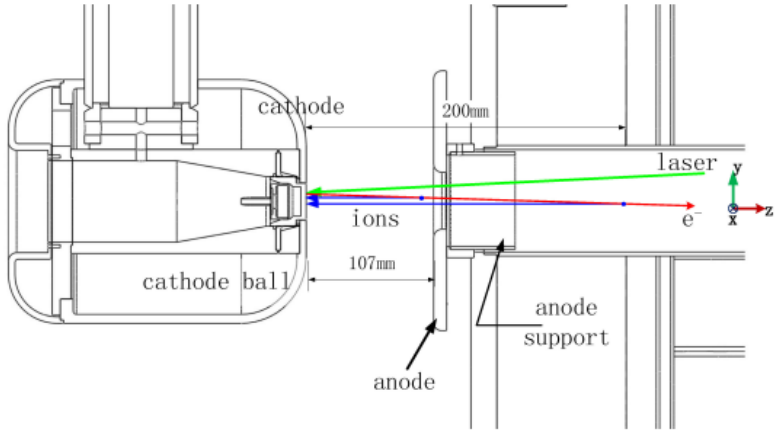
Outline

- 1. Background Introduction
- 2. Physical Model
- 3. Experiment Progress
- 4. Summary
- 5. Further studies

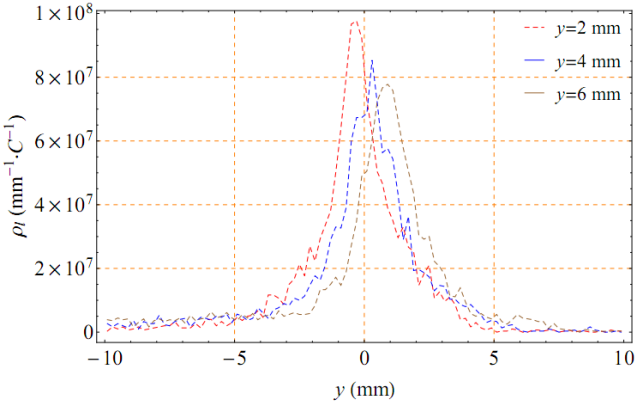
4 Summary

- Physical model: vacuum, temperature and ion back-bombardment (all together)
- Strategies:
  - Beam losses
  - Indium welding
- Present status: 5mA / 0.5h

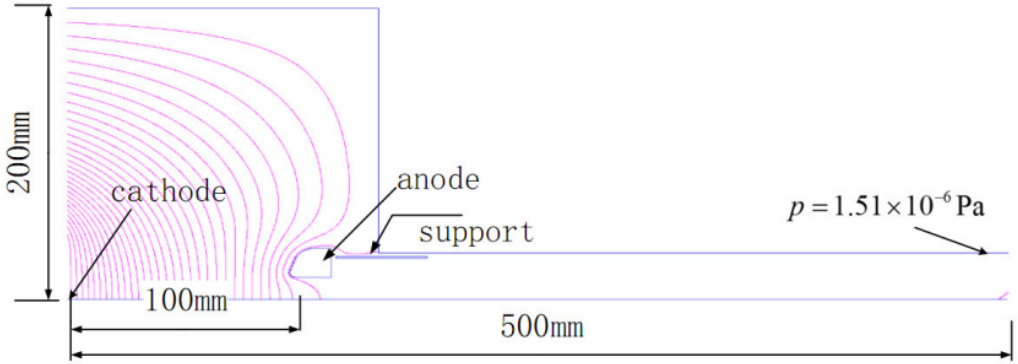
4 Further studies



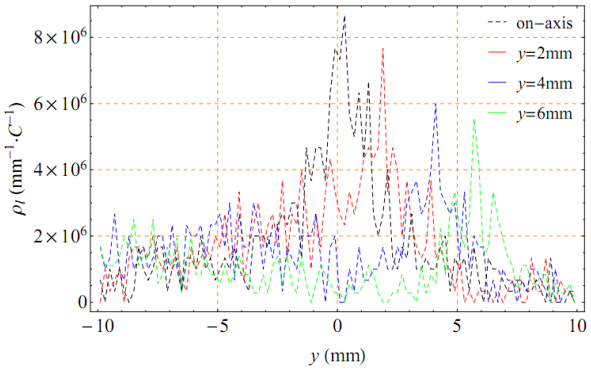
Layout of electron beam emission and ion back bombardment



Line density of H_2^+ ions on the photocathode with laser offset



Basic geometry of the new DC gun and positive potential barrier



Line density with laser offset and positive potential barrier

R J Yang, “Ion tracking in a high-voltage DC photo-gun”, these proceedings, SAP’14,Lanzhou, China (2014)

THE END

THANKS FOR YOUR ATTENTION

Supplement

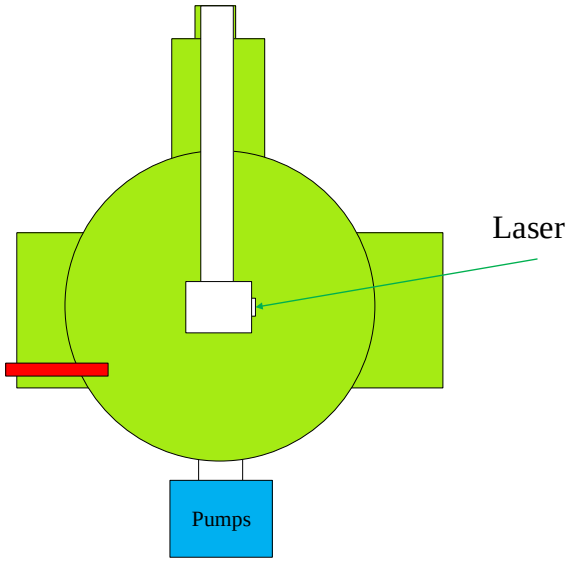
$$\eta(t) = \frac{\eta_0[1-(1-n)k_n t]^{\frac{1}{1-n}}}{1+\kappa t/m}\exp\left(-\frac{Akpt}{m}\right)$$

$$\ln\eta(t) = \ln\eta_0 - \frac{Akpt}{m} - \frac{1}{n-1}\ln[1+(n-1)k_n t] - \ln(1+\kappa t/m)$$

k associated to T

k_n associated to p

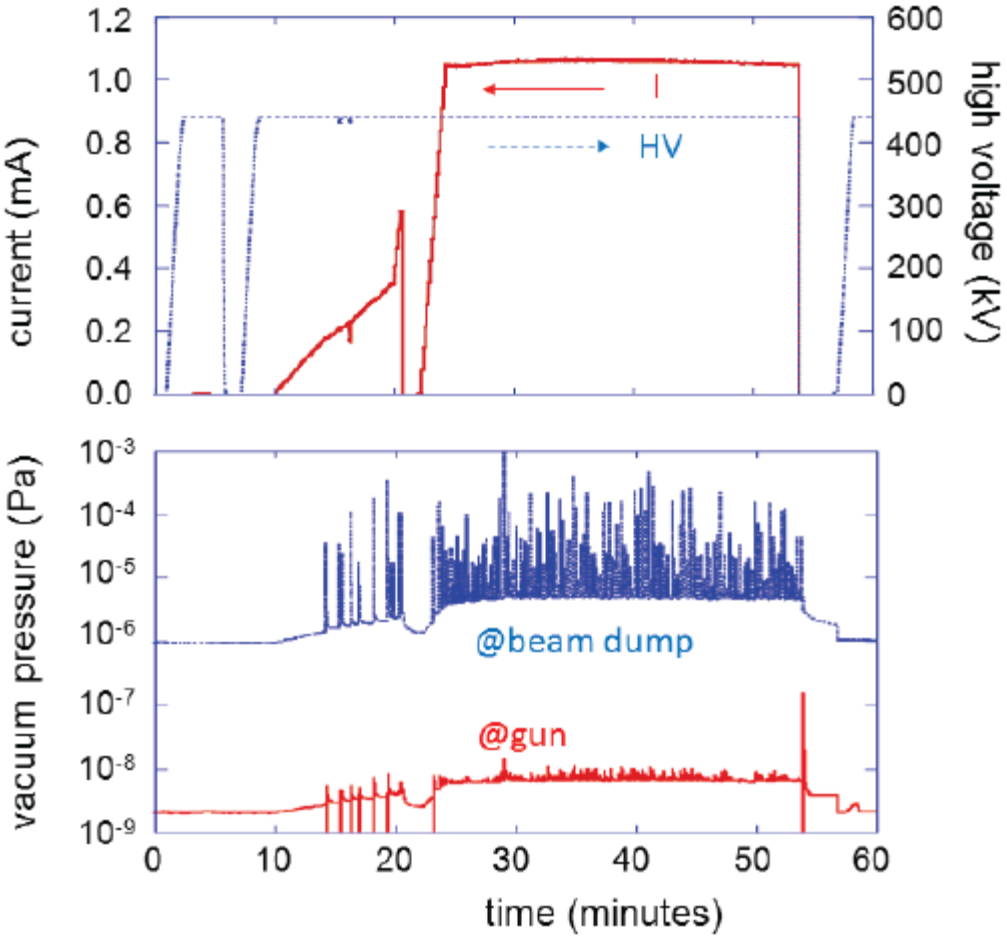
κ associated to T, p and I



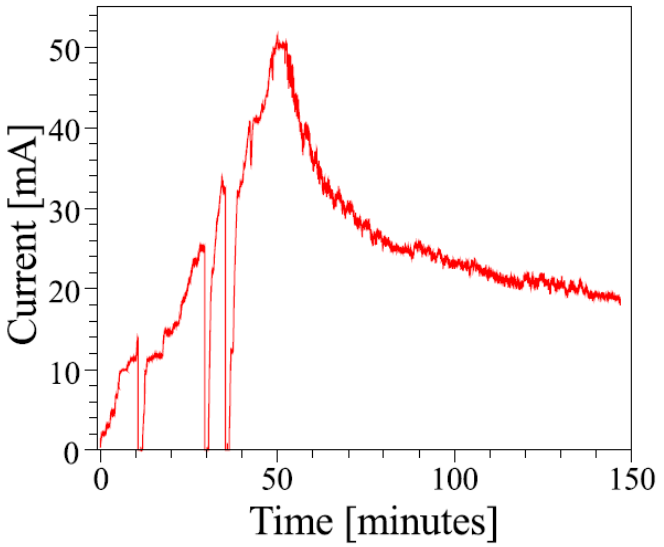
Layout of DC gun

- Vacuum around cahtode： instantaneous
- Vacuum gauge： slow
- Temperature： slow
- Ion back-bombardment： fast

Resent progress in the world



Current output of KEK DC gun



World record of GaAs photocathode

N. Nishimori, IPAC'13, MOPFI019, 2013, 321-323
B. Dunham, et al., Appl. Phys. Lett., 102, 034105 (2013)