# Beam dynamics and measurements of the $e^-$ linac for HUST THz-FEL source

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# A glance of HUST

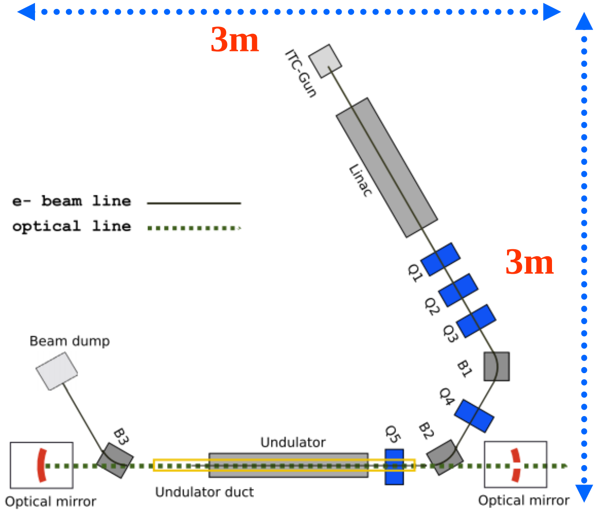

- **National key university, 1200 acres, located in Wuhan, Hubei province, central of China**
- **Established in 1952; in May, 2000, Tongji Medical University and Wuhan Urban Construction Institute are merged into new HUST**
- **~4000 teaching staffs, 22,000 graduate students, 33,000 undergraduate students**

# 1.1 Overview of HUST THz-FEL source

## Scientific parameters of THz-FEL source

| | | | | | |
|---|---|---|---|---|---|
| **Radiation band** | 2~10THz | **Beam energy** | 6~14MeV | $N_u$ | 30 |
| **Macro-pulse width** | 1~4μs | **Bunch charge** | >200pC | $L_u$ | 32mm |
| **Repetition rate** | 1~50Hz | **Bunch length** | 5~10ps | **K** | 1.0~1.25 |
| **Peak power** | ~0.5MW | **Energy spread** | <0.3% | $L_{cav}$ | 2.93m |
| **Average power** | ~1.4W@50Hz | **Nor. Emittance** | <20μm·rad | **ROC** | 1.52m |

Courtesy B. Qin




- Compact structure
- High radiation power
- Tunable wavelength

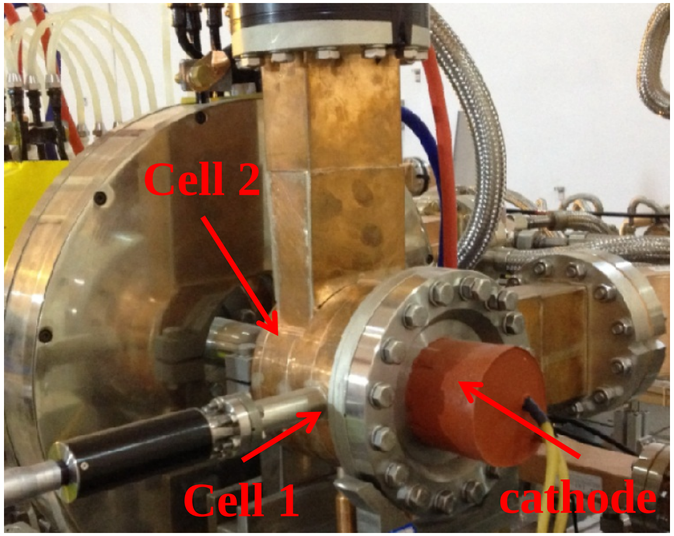
**We intend to make scientific and industrial applications more flexible.**

# 1.2 Compact injector

## 1: Electron gun (**10cm**)

Characteristics:
- Thermal cathode: DC emission
- Cell 1: bunching (**3.5cm**)
- Cell 2: bunching & acceleration (**6.5cm**)

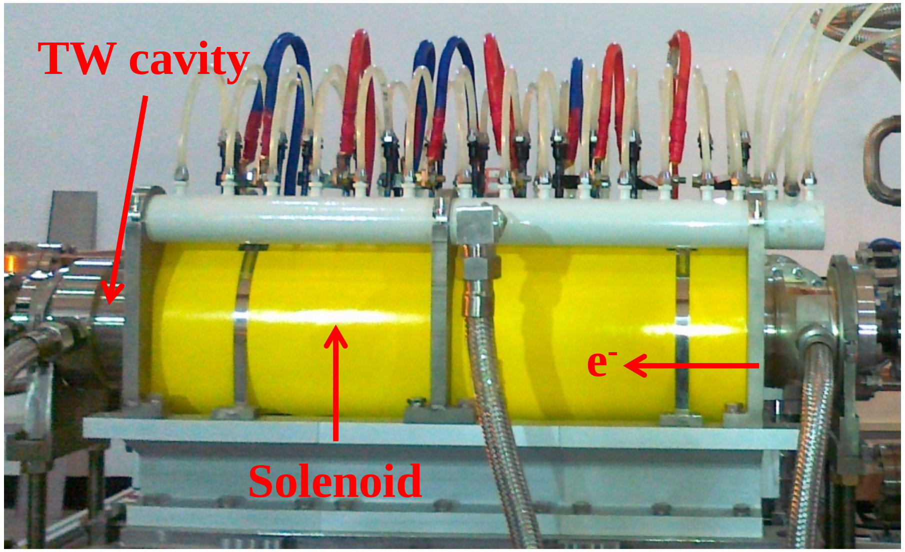
**Merits:**
- ✓ **Independently tunable cells: power & phase**
- ✓ **ps level bunches can be generated**
- ✓ **Compact structure & stable operation**




## 2: S-band Linac (**85cm**)

Characteristics:
- TW; Constant gradient
- 2π/3 mode; 2856MHz
- **Coaxial load**

**Merits:**
- ✓ **No output coupler**
- ✓ **Dimension of solenoid is reduced**
- ✓ **Compact structure**



# 1.3 Design challenges

With the demand of compactness, many challenges were confronted.

1. Optimization of the $e^-$ gun: generate high quality bunches.
2. **Analysis of space charge and beam loading effect: high pulse current from the gun.**
3. Design of coaxial load: absorb remnant power
4. **Optimization of solenoid: operate for different energy beams.**
5. Interference between the fringe field of quadrupoles.

1. Introduction & Background
2. *Transversal motion: focusing*
3. Longitudinal motion: beam loading
4. RF chopper: kick beam tail
5. Beam diagnostics
6. Summary and prospect

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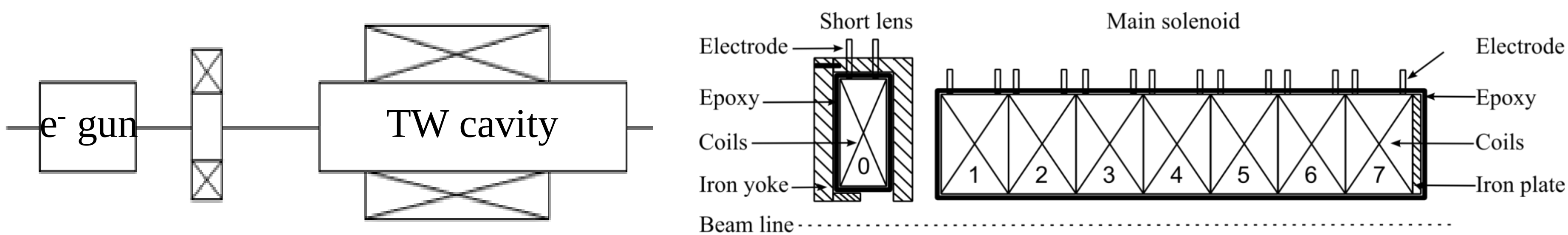
# 2.1 Design of compact solenoid

*Goals:*

- **As compact as possible**.
- **Operated for different beam energy**.
- Fringe field won't affect the cathode.
- Restrain electron beams transversely.
- Possible emittance compensation.
- Central axial field reaches 0.2T.




- Seven independent coils make up the solenoid.
- Measured B-H curve was used.
- Both 2D and 3D models were constructed. Difference between the two models was less than 10Gauss.
- Peak field on-axis could reach 3000Gauss.

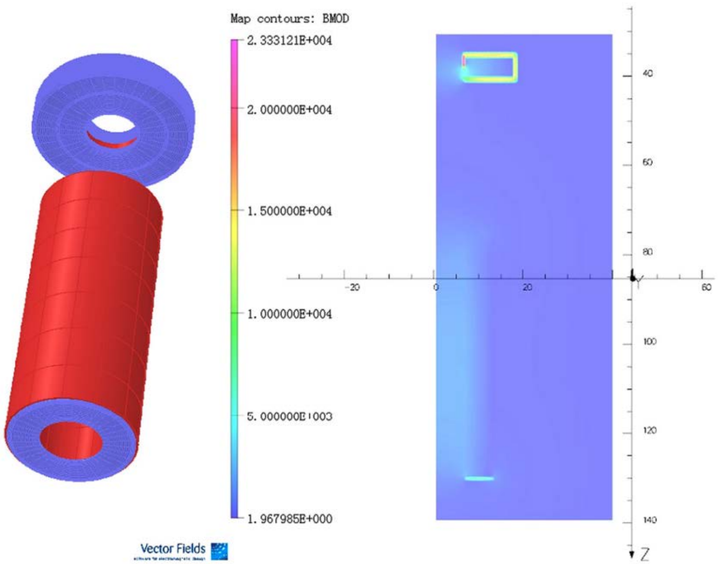
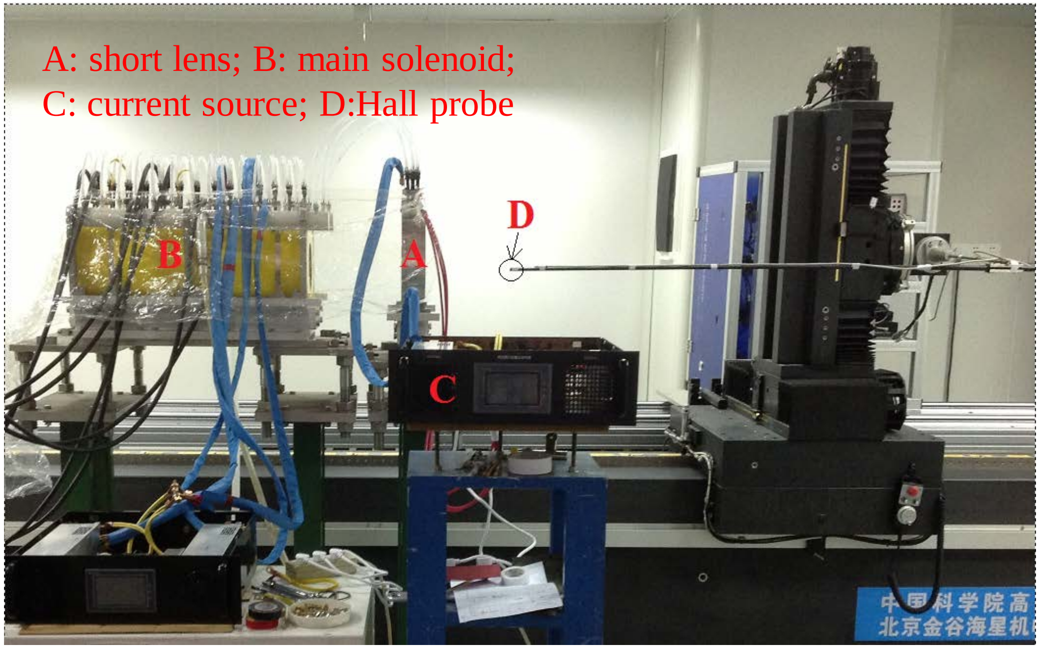
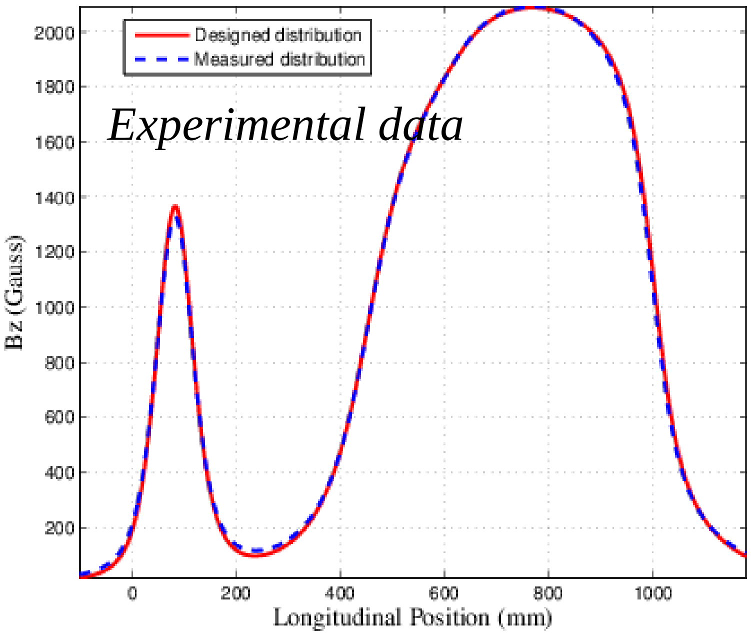



Fig. 5. 3D model and field distribution in the focusing magnets model calculated by OPERA 3D.

# 2.2 Off-line testing



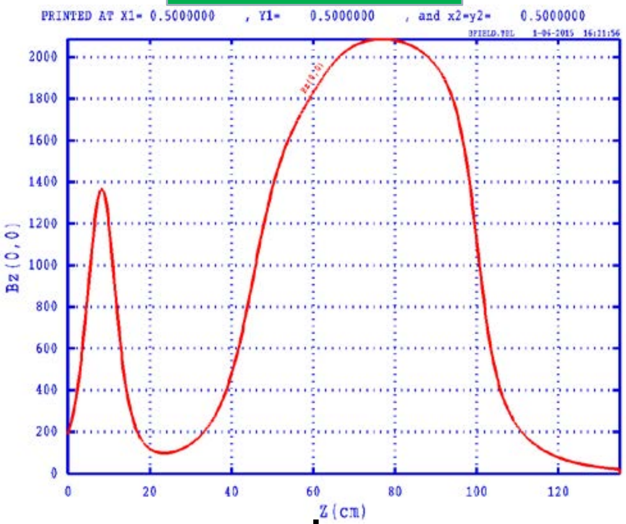

| | |
|---|---|
| Resolution of 3D Hall probe | 0.6 Gauss |
| Accuracy of current source | 0.001A |
| Accuracy and repeatability of actuator | 5μm |
| Speed of actuator | 40mm/s |
| Data sampling rate | 400Hz |

- **Integral field error** between the designed and measured on-axial field was less than **0.4%**.
- **Relative variance** in the paraxial region was less than **0.5%**.

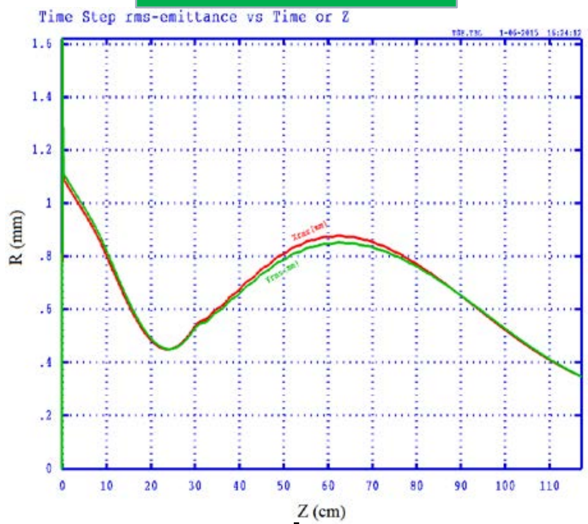
*Qushan Chen et al. NIMA 798 (2015) 74-79.*

# 2.3 Transversal simulation results from Parmela

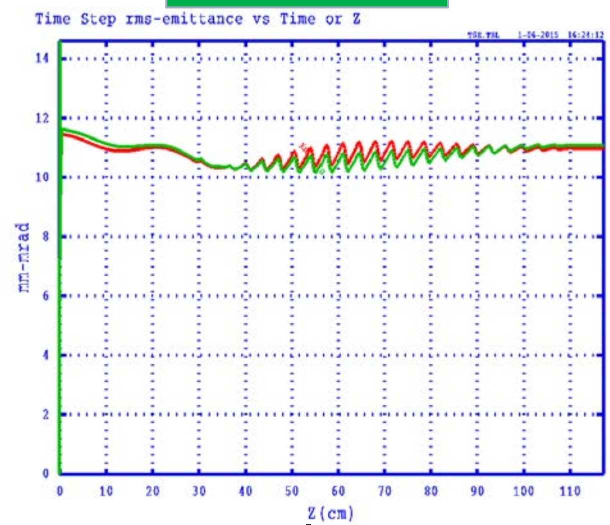
Focusing B field




RMS beam radius




RMS emittance

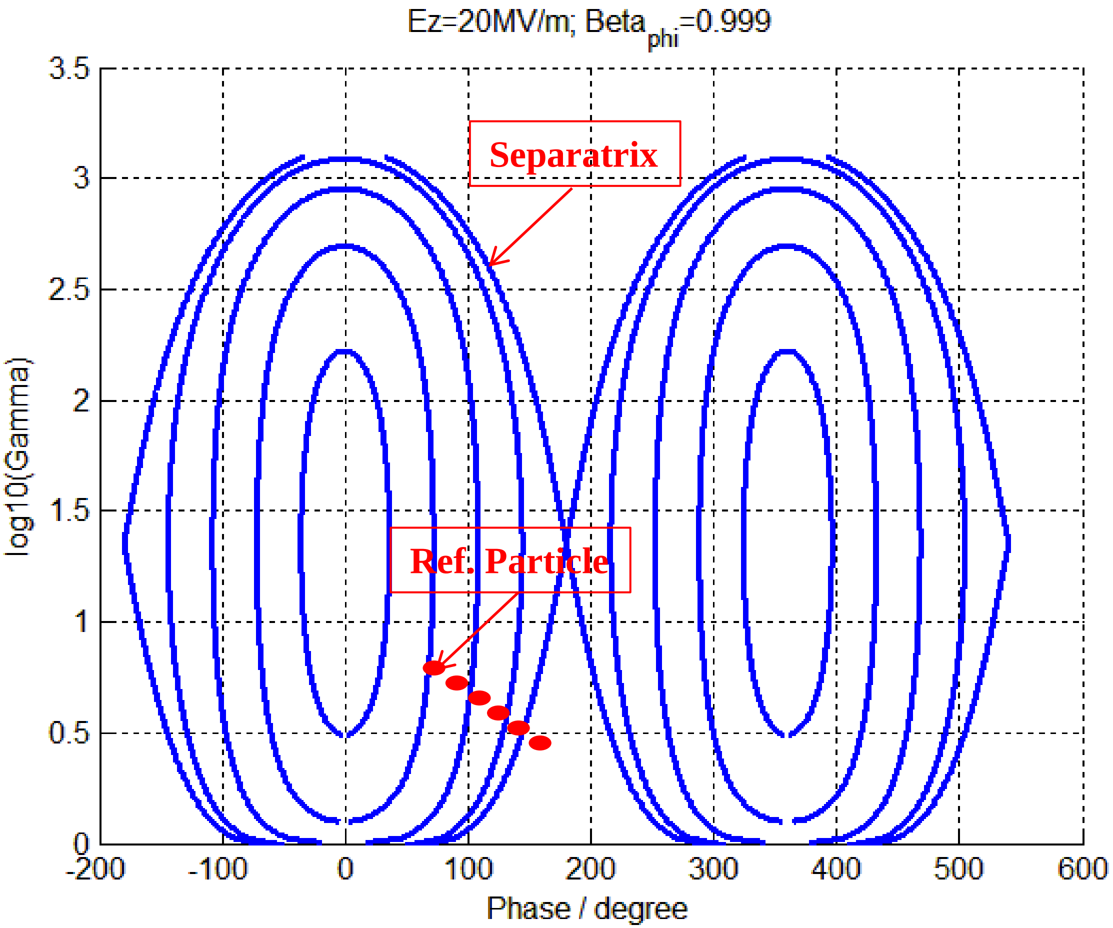



These statistical data refers to the 12ps in the head of one bunch.

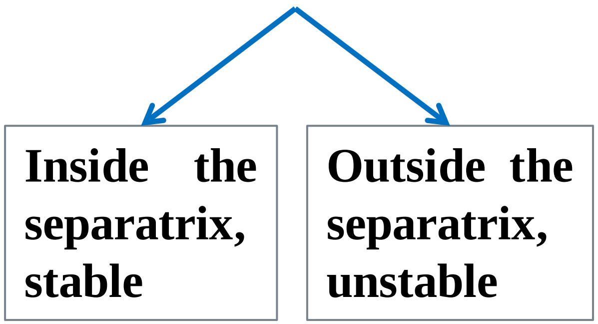
- Current configuration of solenoid has been carried out for different beam energy.
- **No emittance compensation** was observed in the linac.
- **The short lens has limited contribution** to focusing effect. It might be removed in future upgrade.
- **Transverse parameters (radius, emittance) of slice are strongly dependent on longitudinal location.**

# 3.1 Phase shift and beam loss in long bunch

$$H = 2\pi m_0 c^2 \left( \sqrt{\gamma^2 - 1} - \frac{\gamma}{\beta_\varphi} \right) + e\lambda E_z \cos\varphi$$ (in sine convention)




Injected particles




Reference energy=2.6MeV
Reference phase=$85^0$
Bunch length>$100^0$

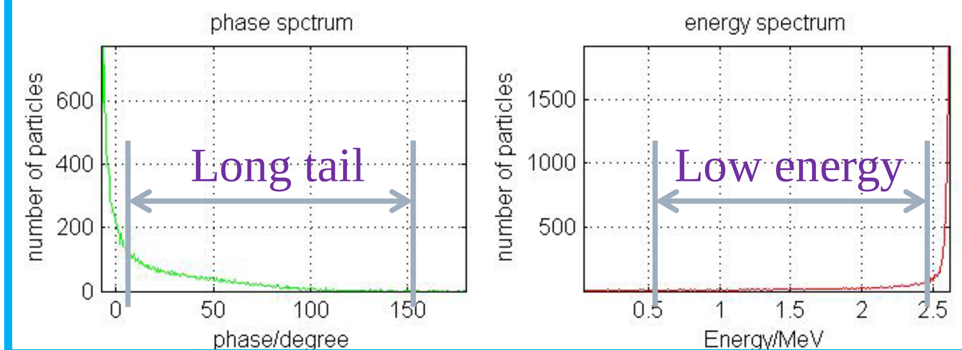
- Phase shift
- Particle loss

# 3.2 Long bunches from the e⁻ gun

At the beginning, we expected Gaussian distribution and short bunch with charge of 200pC from the e⁻ gun. But the simulated result was a big difference.

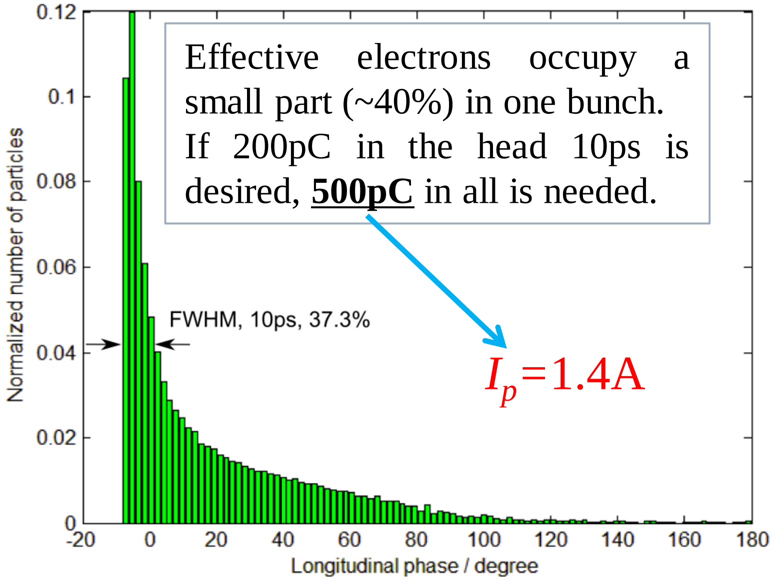
**Predefined bunch from the gun** **V.S.** **Simulated output of the gun**

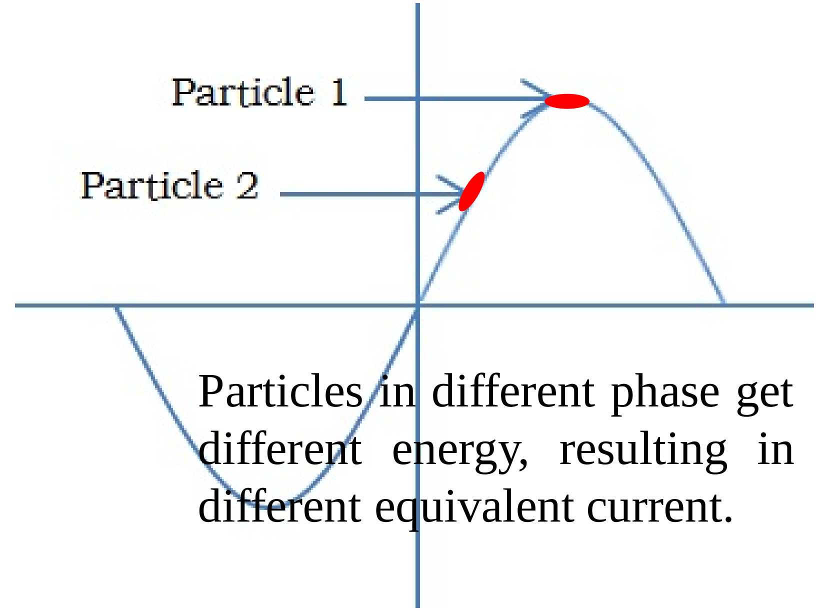
- **Gaussian distribution**
- **Short bunch: 5~10ps**
- **Charge: 200pC**




Bunches from the e⁻ gun can be divided into two parts: **head** and **tail**. Head is the useful portion, ~10ps, 200pC. It is the tail portion that makes a problem.

Pulse current is computed from the **charge in one bunch and RF period**. ($I_p$)
Beam loading current is the **equivalent current** that **dissipates RF power** in a cell. ($I_b$)




Particles in different phase get different energy, resulting in different equivalent current.

Equation of power flow:

$$dP_i = \left(-2\alpha_i P_i - I_b E_i\right) dz$$

**Beam loading current**

1. For short bunches: $I_b \approx I_p$
2. For long bunches, there may have serious beam loss and phase shift.

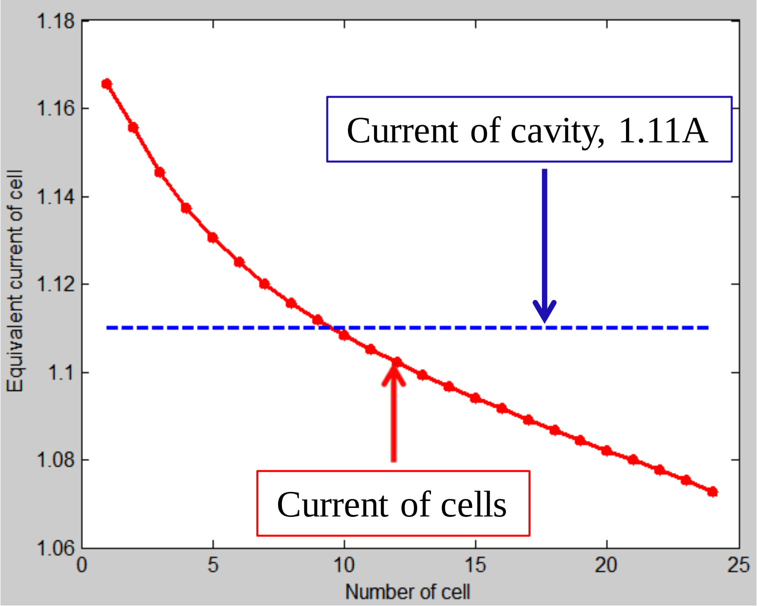
**Rigorous analysis of beam loading**

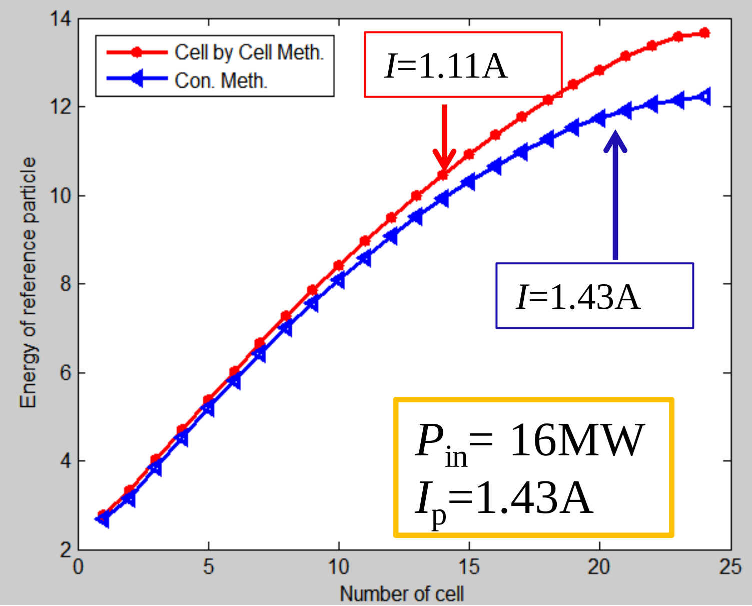
# 3.4 Algorithm: Cell-by-Cell, 1D longitudinal motion

Equation of power flow: $\Delta P_i = -2\alpha_i P_i D - \frac{Q_i}{M_i T}\sum_{j=1}^{M_i}\int_0^D E_i \cos\varphi_i dz$

RF power dissipated on wall

RF power dissipated by beam



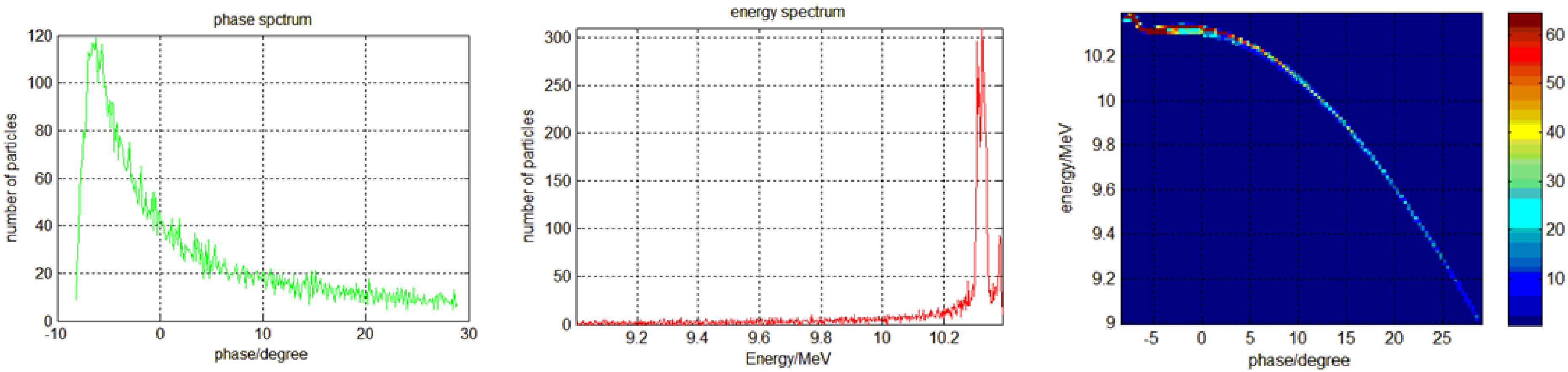

**The Cell-by-Cell algorithm has been verified when $P_{in}$=11MW, $I_p$=0.74A:**

| Conventional alg. | Cell-by-Cell alg. | Measured |
|---|---|---|
| 12.2MeV | 13.2MeV | 13.5MeV |

*Qushan Chen et al. Chin. Phys. Lett. 31 (2014) 012902.*

# 3.5 Longitudinal simulation results from Parmela

## Longitudinal spectrum from the linac:

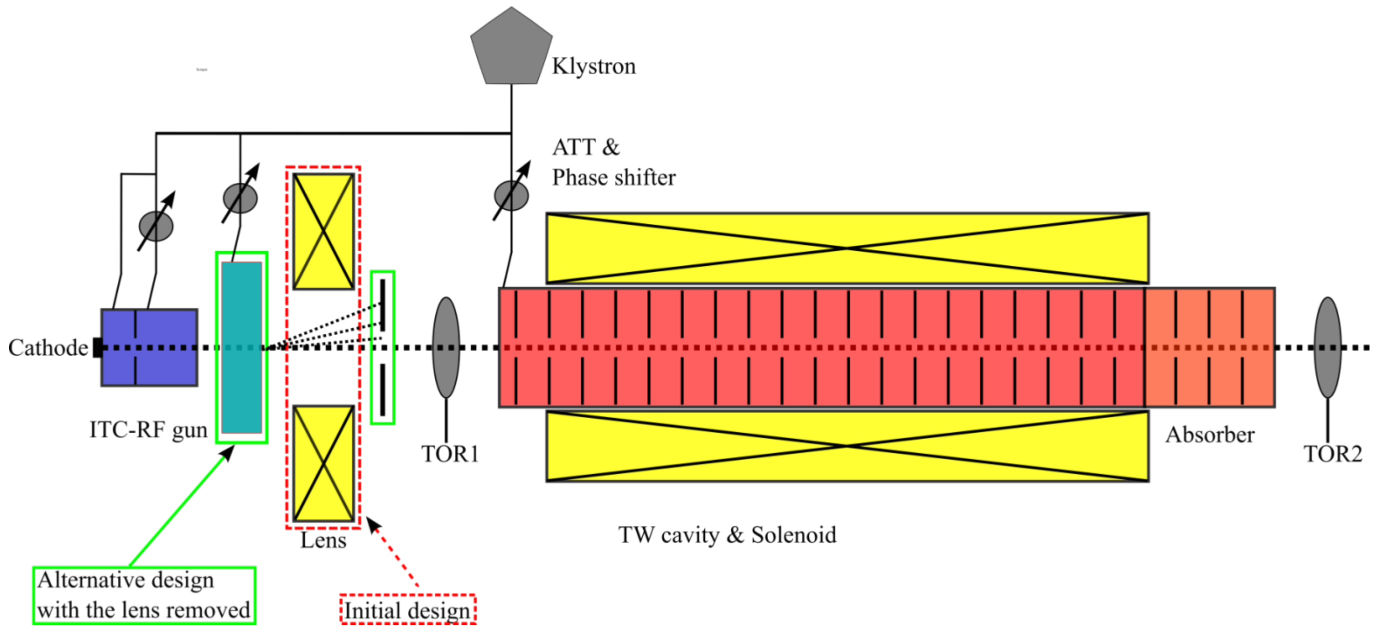



$E_{ref}$=10.3MeV, $\Delta E/E$=0.3%, $\tau$=5ps (FWHM)

- It's easy to obtain $e^-$ beam ranging from 6~14MeV by changing the input power.
- Energy spread (FWHM) can be optimized to **less than 0.3%** when beam energy is **larger than 8MeV**, but difficult when beam energy goes low.
- **Long beam tail** still exists. Head particles are less than 50%.

# 4.1 RF chopper: a solution to long beam tail

RF chopper scheme is proposed to cut off the beam tail before they enter the linac, aiming to mitigate beam loading effect and protect the TW cavity.



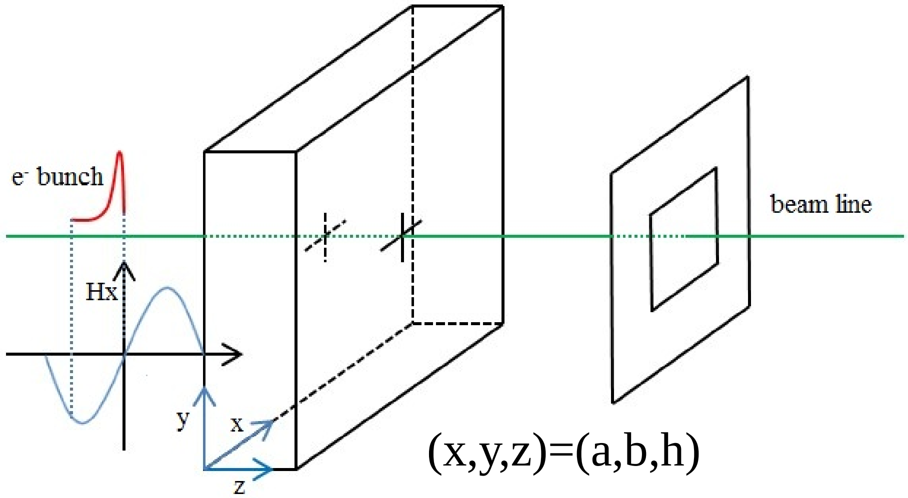

Resonant cavity

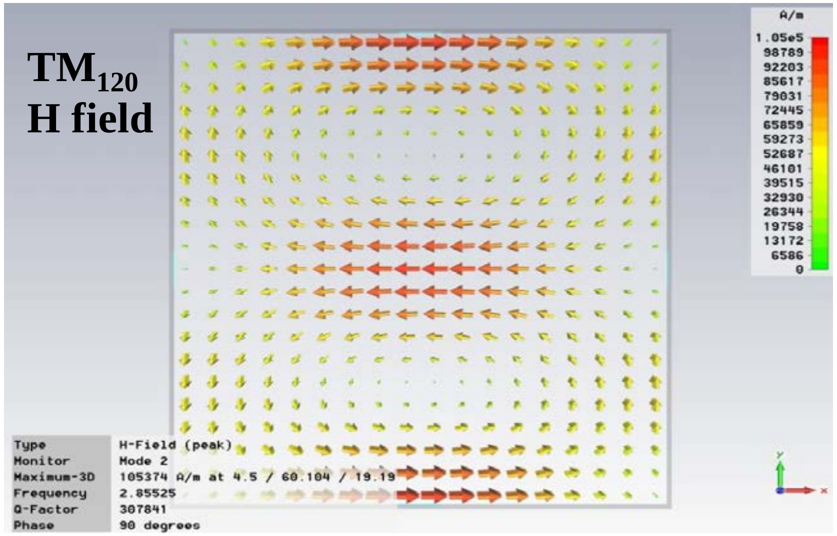
+

Scraper

→

- The short lens is removed.
- Longitudinal distribution is unchanged.
- The same RF power source is used.
- All cavities work on the same frequency.




$$H_x = j\frac{\omega\varepsilon}{K_c^2}\left(\frac{2\pi}{b}\right)E_0 \sin\left(\frac{\pi}{a}x\right)\cos\left(\frac{2\pi}{b}y\right)$$ → Deflection force

- Operated in $TM_{120}$ mode; $\boldsymbol{H_x}$ is the only component on central axis.
- Head particles pass the chopper freely.
- Tail particles will be removed.

**Optimum dimension:**

$$a = \lambda$$

$$b = 2\sqrt{3}\lambda/3$$

$$h^{-1}\tan\left(\frac{\omega h}{2v_0}\right) = \frac{\omega}{v_0}$$

→ **Maximum efficiency**

(Q value is not varied with dimensions.)

Define excitation time:

$$t_{exc} = \frac{2Q_L \ln 10}{\omega}$$

Time consumed to build up 90% of steady state.

If copper is used, the unloaded Q is about 18,600, resulting in a filling time of 2.4μs. Filling time less than 0.3μs is desired. Q must be reduced to 2340.

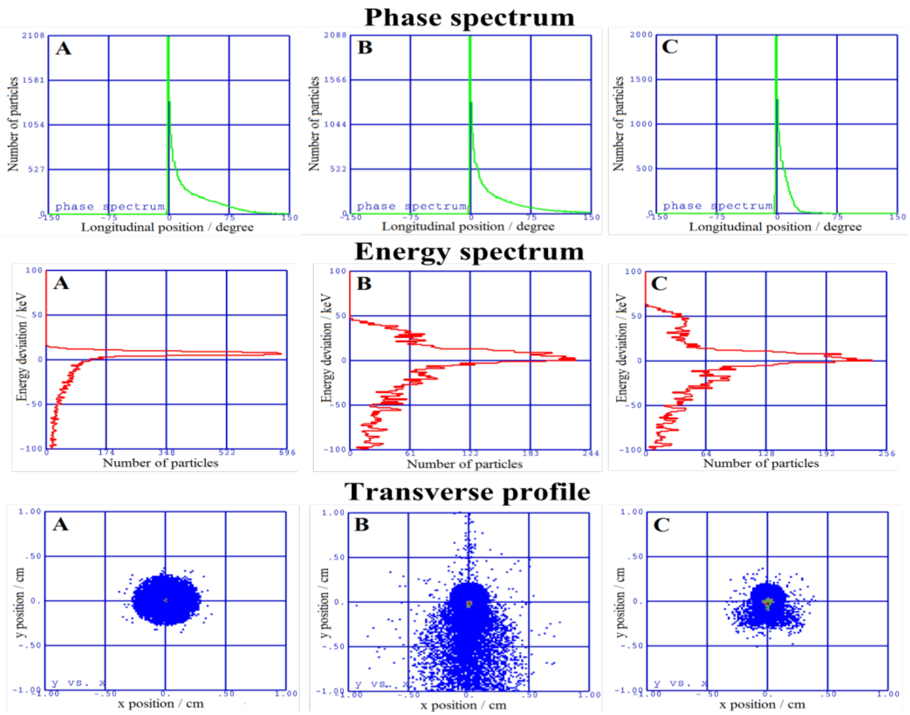
Two methods to reduce the filling time:

1) Cavity material with relatively high loss factor;
2) **High loss factor material coated on the inner wall**.

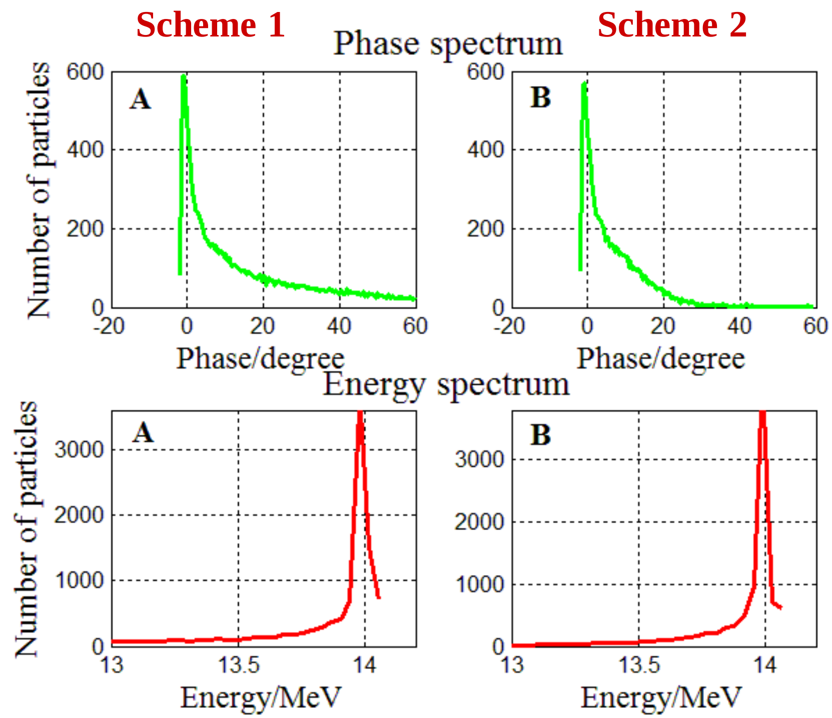
Physical parameters of the RF chopper system.

| | |
|---|---|
| Resonant frequency | 2856 MHz |
| Resonator dimension $(x, y, z)$ | 105 mm × 121.2 mm × 38.4 mm |
| Unloaded quality factor | 2000 |
| Excitation time | 0.25 μs |
| Input power | 0.2 MW |
| Drift length | 100 mm |
| Scraper dimension $(x, y)$ | 4 mm × 3.6 mm |
| Maximum deflection voltage | 0.12 MV |

# 4.4 Beam quality improvement




Gun exit | Scraper | Linac entrance

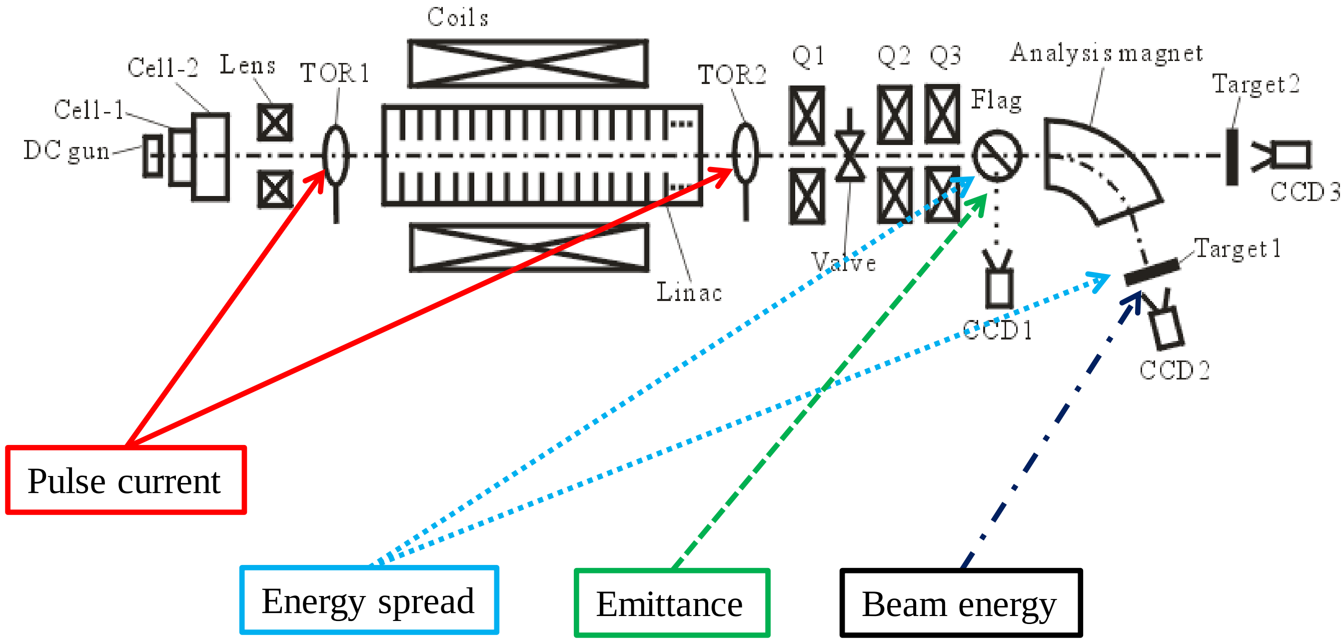



Linac exit

| Parameters | Scheme 1 | Scheme 2 |
|---|---|---|
| Reference energy (MeV) | 2.6 | 2.6 |
| Energy spread (FWHM) (%) | 0.67 | 0.69 |
| Norm. emittance ($x$) (μm · rad) | 8.319 | 8.326 |
| Norm. emittance ($y$) (μm · rad) | 8.633 | 13.385 |
| Charge (pC) | 210 | 210 |
| Bunch length[a] (ps) | 100 | 30 |
| Bunch charge[a] (pC) | 525 | 282 |

- Operation fre.=2856MHz
- Input power: 0.2MW
- 105×121.2×38.4 (mm)
- **>78% tail portion is removed**
- **Quality of head portion is preserved**

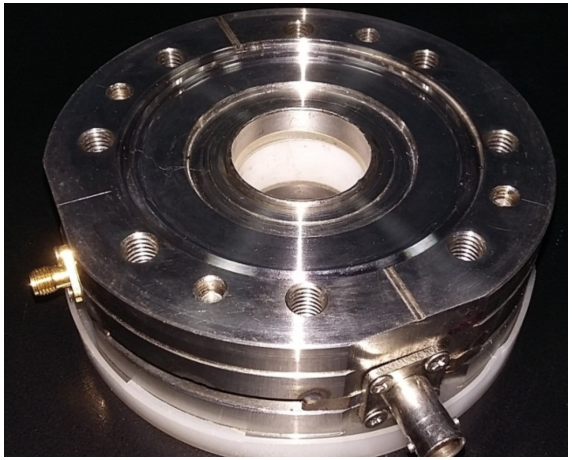
*Qushan Chen et al. NIMA 755 (2014) 78-84.*

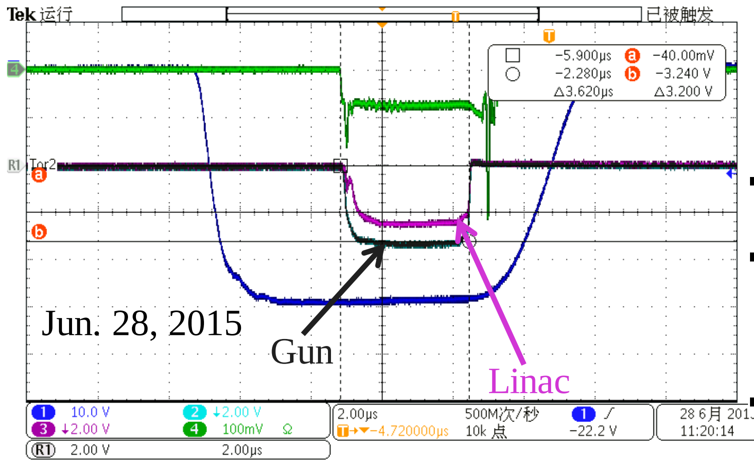



- **Pulse current**: Fast Current Transformer (**FCT**) × 2
- Beam energy: **Target1+Bend**
- Energy spread: **Flag+Target1+Bend**
- Emittance: **Flag+Quadrupole**

# 5.2 Pulse current & emittance

## (1)Pulse current

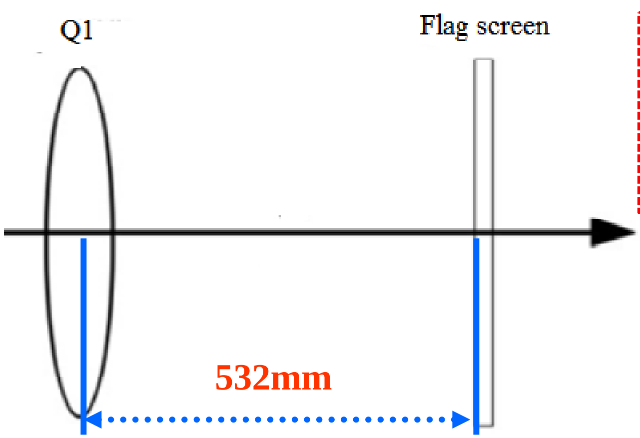




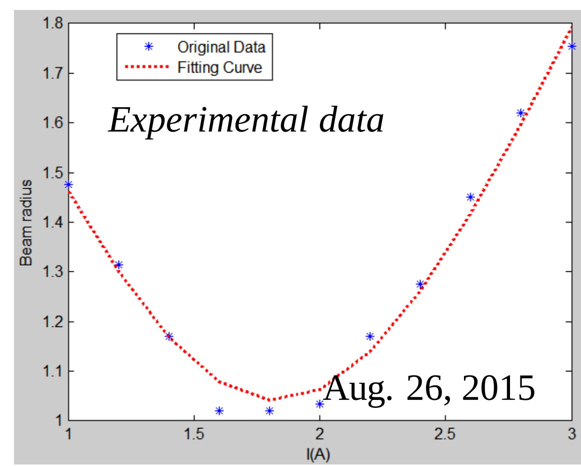

Sensitivity of FCT is 4.3V/A.

| | Pulse length | Current |
|---|---|---|
| Tor 1 | 3.8µs | 0.74A |
| Tor 2 | 3.8µs | 0.56A |

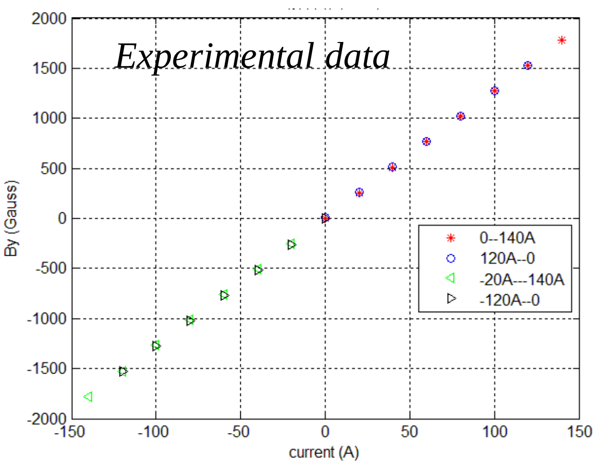
## (2)Emittance: scanning of focusing strength




Current of $Q_1$ varies from 1A to 3A, with increment of 0.2A and then measure the beam spots on the flag screen.

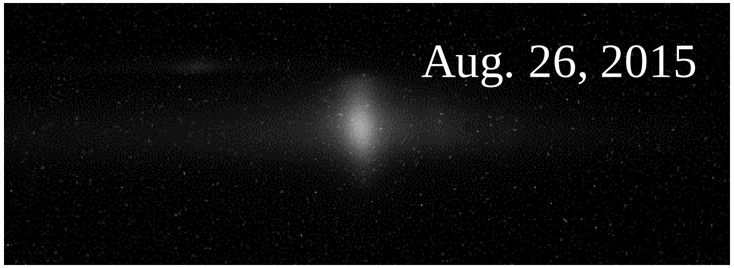


## (3)Beam energy




$$B_y(\text{Gauss}) = 12.67 I(\text{A}) + 4.108$$

Beam spot on Target1, seen by CCD2




$$I_x = 80\text{A} \longrightarrow W = 9.57\text{MeV}$$

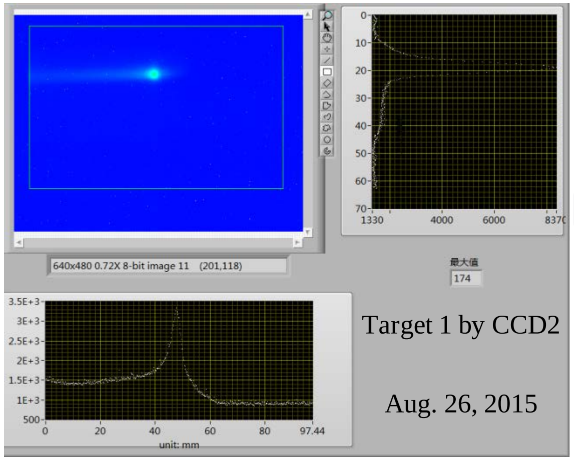
## (4)Energy spread

$$\left(\frac{\Delta p}{p}\right)_{in} = \sqrt{\sigma_{out}^{\ 2} - (m_{11} \cdot \sigma_{in})^2} \ / \ m_{13}$$

| $\rho$ (mm) | $\theta$ (Deg) | $a$ (mm) | $b$ (mm) | $m_{11}$ | $m_{12}$(mm) | $m_{13}$ (mm) |
|---|---|---|---|---|---|---|
| 320 | 74.69 | 443 | 417.4 | -0.9939 | -0.0214 | 638 |

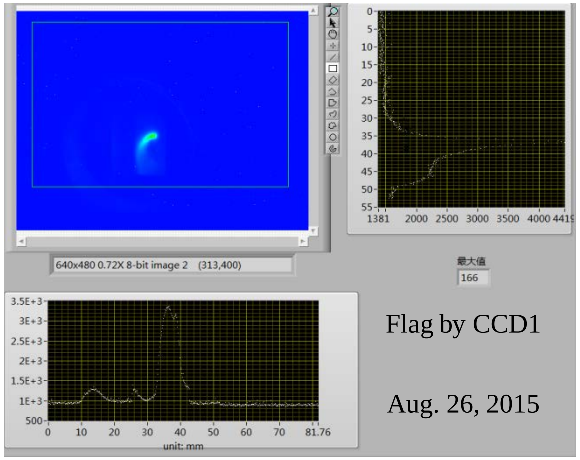
$$\sigma_{in} = 6.39\text{mm}, \sigma_{out} = 6.66\text{mm}$$

$$\frac{\Delta W}{W} = \frac{\Delta p}{p} = 0.31\%$$




Target 1 by CCD2

Aug. 26, 2015




Flag by CCD1

Aug. 26, 2015

1. Introduction & Background
2. Transversal motion: focusing
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6. *Summary and prospect*

# Summary of my work and Prospect

## Summary

- A cell-by-cell algorithm was proposed to analyze the beam loading effect and it has been verified by experiment.
- A compact solenoid was designed and tested. The testing results showed very good agreement with the design.
- Start-to-end simulation of the injector was performed.
- Conceptual design of a RF chopper system was carried out to cut off the beam tail.

## Prospect

- Technical design of the chopper cavity: coupler, Q value etc.
- Interaction among a series of bunches for their phase shift during acceleration.
- Performance reduction due to the overlap of quadrupoles' fringe field.
- Emittance compensation in the $e^-$ gun.
- More flexible methods for beam diagnostics.

# List of Publications

- **Qushan Chen**, Bin Qin et al. "Design and testing of focusing magnets for a compact electron linac". *Nuclear Instruments and Methods in Physics Research A* 798 (2015) 74-79.
- **Q. Chen**, B. Qin, P. Tan Y. Pei et al. "Design of RF chopper system for improving beam quality in FEL injector with thermionic gun". *Nuclear Instruments and Methods in Physics Research A* 755 (2014) 78-84.
- **CHEN Qu-Shan**, PEI Yuan-Ji, HU Tong-Ning, QIN Bin. "A novel method for rigorously analyzing beam loading effect based on the macro-particle model". *Chinese Physics Letters*, vol. 31, No. 1 (2014) 012902.
- Tongning Hu, Yuanji Pei, Bin Qin, Ping Tan, **Qushan Chen,** Lei Yang, and Ji Li. "Study of beam transverse properties of a thermionic electron gun for application to a compact THz free electron laser". *Review of Scientific Instruments*, **85**, 103302 (2014)
- HU Tong-Ning, **CHEN Qu-Shan**, PEI Yuan-Ji et al. "Physical design of FEL injector based on the performance-enhanced EC-ITC RF gun". *Chinese Physics C*, vol. 38, No. 1 (2014) 018101.
- **Q. Chen**, T. Hu, B. Qin et al. "Focusing magnetic field design for a FEL lianc". *Proceedings of IPAC2013*, Shanghai, China, pp. 1949-1951.
- Han Zeng, **Qushan Chen** et al. "Physical design of beam transport line of a compact terahertz FEL". *Proceedings of IPAC2013*, Shanghai, China, pp. 1952-1954.

# Acknowledgement

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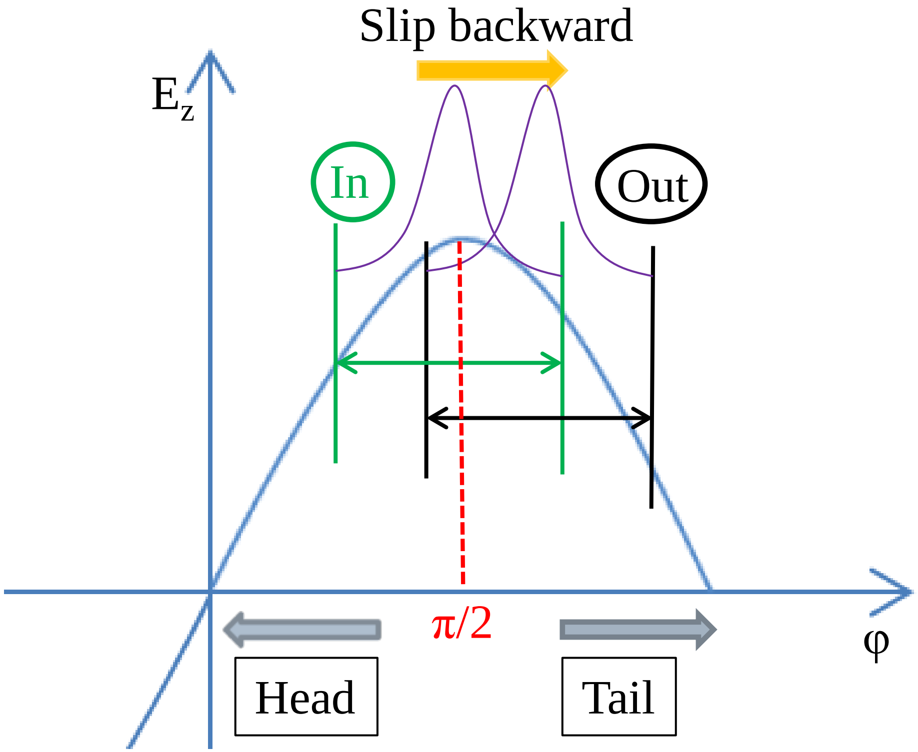
Full respect goes to Prof. **M.W. Fan**, **Y.J. Pei**, **K.J. Fan**, **B. Qin**, **P. Tan**, **Y.Q. Xiong**, **G.Y. Feng**, **L. Shang**, **X.Q. Wang**, **Y.L. Hong**, **K. Jin** and Dr. **T.N. Hu** for their significant and continuous contribution to the project. We would also like to thank all related colleagues for their hard work.

# Thank you for attention!

**Bunches will slip backward during acceleration.**




Phase factor:

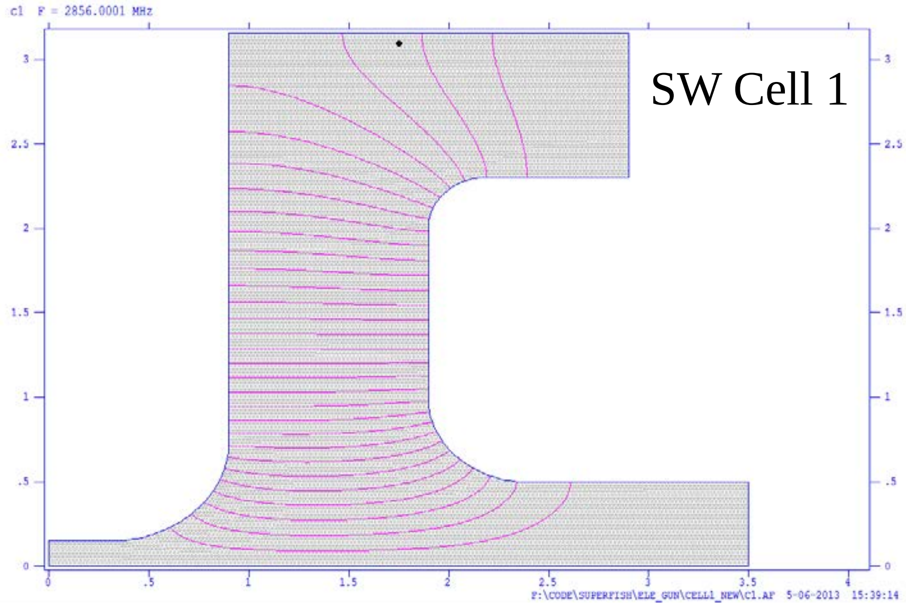
$$\phi_i = \frac{1}{D}\sum_{j=1}^{M_i}\int_0^D \cos\varphi_i^{\ j} dz$$

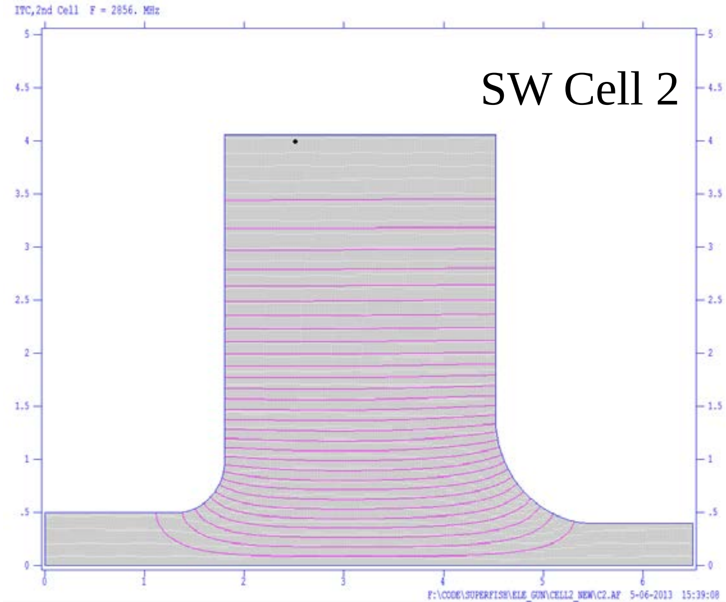
**Cell current varies with $\phi_i$.**

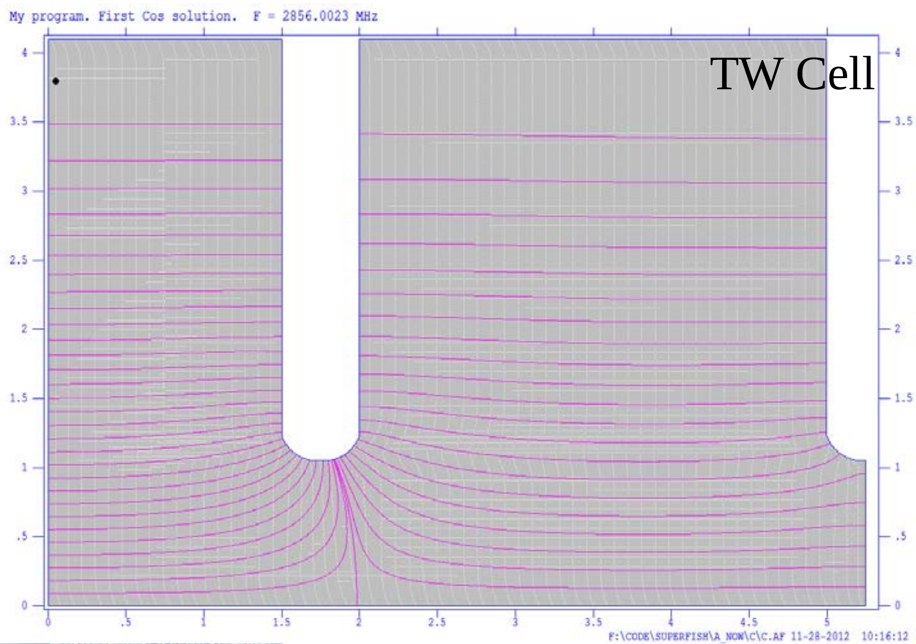
- For short bunches, current of cell should increase along the structure if accelerated in stable phase (0, Pi/2)
- For long bunches, the situation will be underdetermined.

- Particles with φ<π/2 make the cell current increase
- Particles with φ>π/2 make the cell current decrease
- Contribution of particles just refers to acceleration phase, has nothing to do with their energy.

# Supplementary




| | Q | Rs | $f_0$ |
|---|---|---|---|
| SW 1 | 6080 | 17MΩ/m | 2856MHz |
| SW 2 | 13155 | 50MΩ/m | 2856MHz |
| TW | 13948 | 62MΩ/m | 2856MHz |

# Supplementary

$$K_c = k = \sqrt{(\pi/a)^2 + (2\pi/b)^2}$$

$$\omega_{E_z} = \frac{1}{4}\varepsilon E_0^{\ 2}\sin^2\left(\frac{\pi}{a}x\right)\sin^2\left(\frac{2\pi}{b}y\right)$$

$$\omega_{H_x} = \frac{1}{4}\frac{\varepsilon}{K_c^{\ 2}}\left(\frac{2\pi}{b}\right)^2 E_0^{\ 2}\sin^2\left(\frac{\pi}{a}x\right)\cos^2\left(\frac{2\pi}{b}y\right)$$

$$\omega_{H_y} = \frac{1}{4}\frac{\varepsilon}{K_c^{\ 2}}\left(\frac{\pi}{a}\right)^2 E_0^{\ 2}\cos^2\left(\frac{\pi}{a}x\right)\sin^2\left(\frac{2\pi}{b}y\right)$$

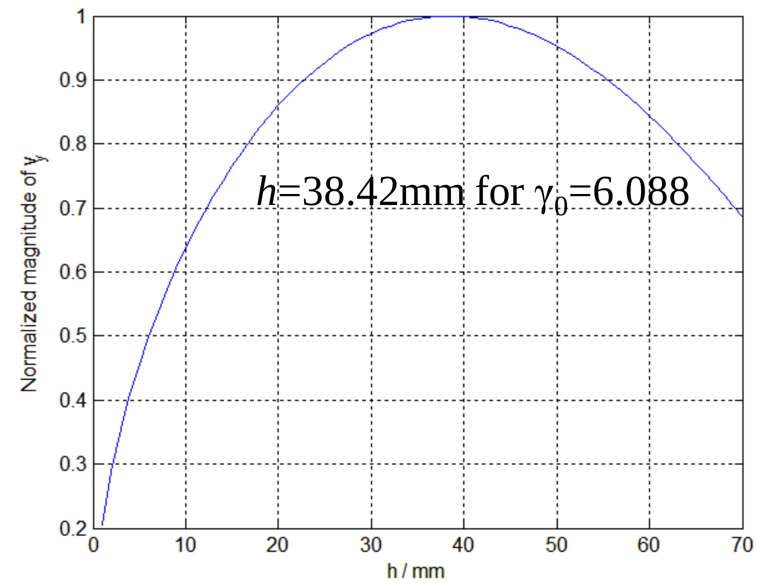
$$U = \int_0^h\int_0^b\int_0^a\left(\omega_{E_z} + \omega_{H_x} + \omega_{H_y}\right)dxdydz = \frac{1}{8}\varepsilon V E_0^{\ 2}$$

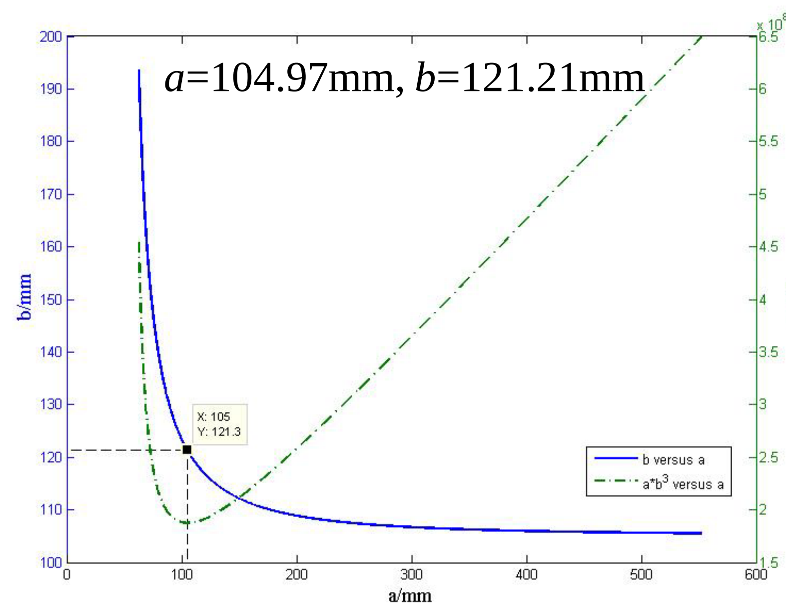
$$E_0 = \sqrt{\frac{8QP_l}{\omega\varepsilon V}}$$

$$H_x = \frac{4\pi}{K_c^{\ 2}}\sqrt{\frac{2\omega\varepsilon P_l Q}{h}}\cdot\sqrt{\frac{1}{a\cdot b^3}}\sin\left(\omega t + \varphi_0\right)$$

$$v_y = \int_0^{h/v_0}\frac{e\mu_0 v_0 H_{mx}}{m_0\gamma_0}\sin\left(\omega t + \varphi_0\right)dt$$

$$= \left[\frac{2e\mu_0 v_0 H_{mx}}{\omega m_0\gamma_0}\sin\left(\frac{\omega h}{2v_0}\right)\right]\sin\left(\frac{\omega h}{2v_0} + \varphi_0\right)$$



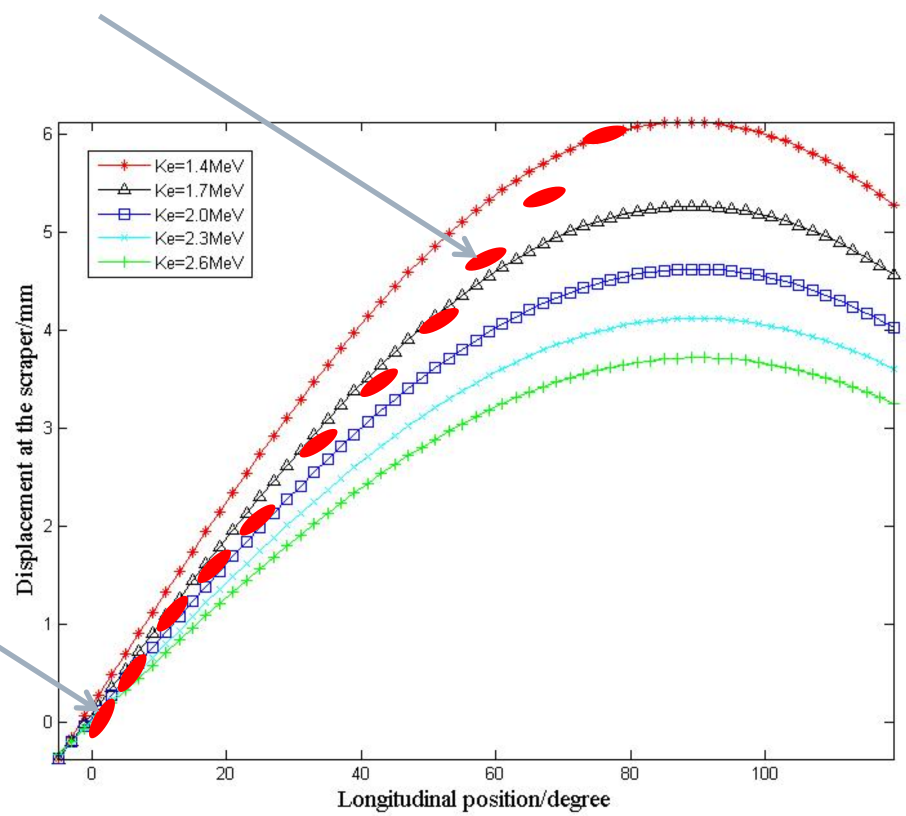



# Supplementary

The lagging particles will have less energy, so the sensitivity is enhanced further.

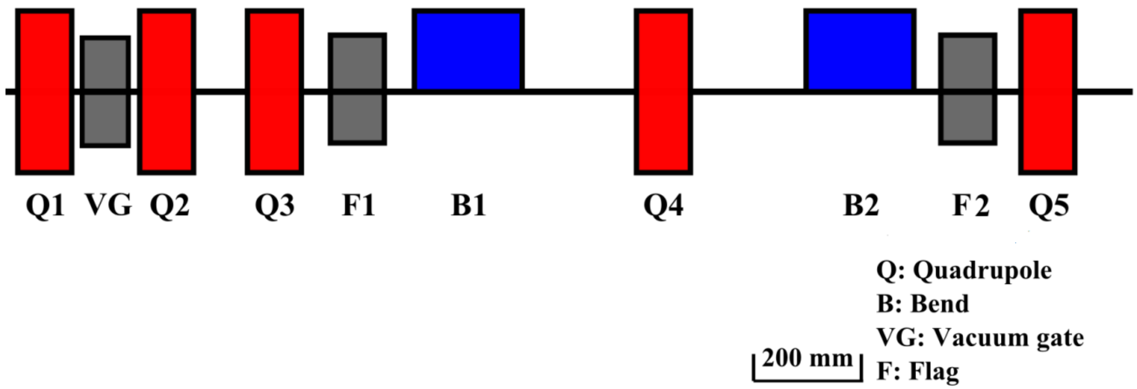
$$S = \Delta y/L = \tan\left(v_y/v_0\right)$$

Reference particle
No deflection




Transverse displacement at 100mm downstream for $H_{mx}$=$10^4$A/m

# Supplementary




| Beta_x | Beta_y | Alpha_x | Alpha_y | D_x |
|---|---|---|---|---|
| 1.2 m | 0.26 m | 1.0 | 0.546 | 0 |