My research activities on RF gun and beam dynamics in the past

By Xiangkun LI

- ✓ Come from China and had been in Japan and France for several years
- ✓ Start as a new member of PITZ group from August 1, 2018
  - Disciplinary supervisor: Dr. Frank Stephan
  - Technical supervisor: Dr. Mikhail Krasilnikov

Contents

- Education background
- Research experiences
  - RF guns
  - THz FEL beamline
  - Laser plasma accelerator
- Expectation

Education background

Aug, 2005-Jul, 2009

B.S. in *Engineering Physics*

Department of Engineering Physics, Tsinghua University, Beijing, China

Oct, 2010-Mar, 2012

M.S. in *Physics*

Department of Physics, Tohoku University, Sendai, Japan

TOHOKU UNIVERSITY

Sep, 2009-Jul, 2015

Ph.D. in *Nuclear Science and Technology*

Department of Engineering Physics, Tsinghua University, Beijing, China

Research experiences

For most of my career, I have been working on an electron beam interacting with some kind of EM fields, and how to transport it without degrading its quality

- ✓ Back-bombardment effect in a thermionic RF gun (Master’s degree)
- ✓ Field emission cathode based study in RF guns (PhD’s degree)
- ✓ Optimization and commissioning of a THz FEL beamline (>1 year)
- ✓ Beam quality preservation in staged laser plasma accelerators (~ 2 years)

Research experience (1)

Oct, 2010-Mar, 2012

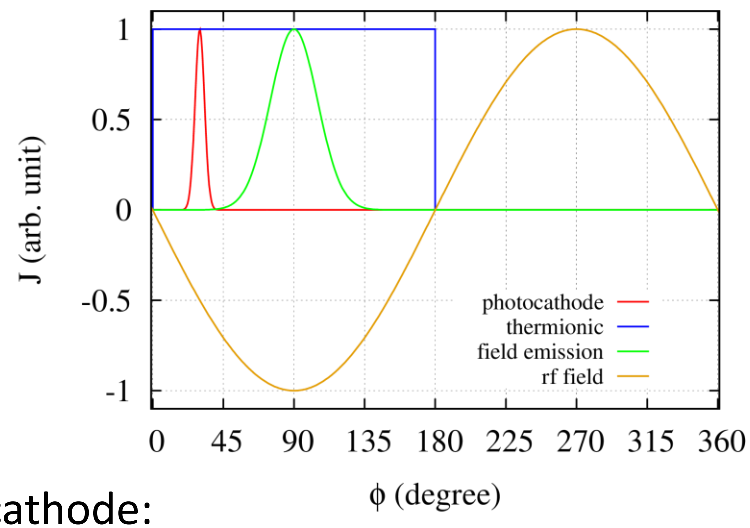
Study of back-bombardment (B.B.) effect in a thermionic RF gun

Supervisor: Prof. Hiroyuki Hama

TOHOKU UNIVERSITY

Motivation

B. B. effect ⇒ **Cathode overheated** ⇒ **Beam current increased**



Emission of electrons from different cathodes in RF field

For thermionic cathode:

- 🙂 the emission occurs in each RF cycle, therefore providing high average current
- ☹ the B.B. effect causes the overheating of the cathode and results in more and more emissions

Research experience (1)

Oct, 2010-Mar, 2012

Study of back-bombardment (B.B.) effect in a thermionic RF gun

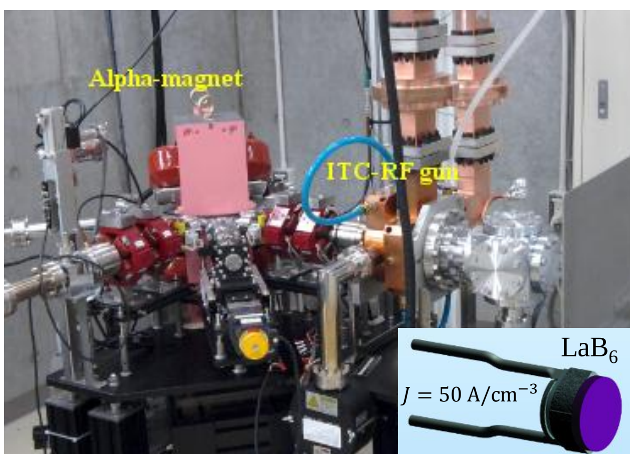
Supervisor: Prof. Hiroyuki Hama

Motivation

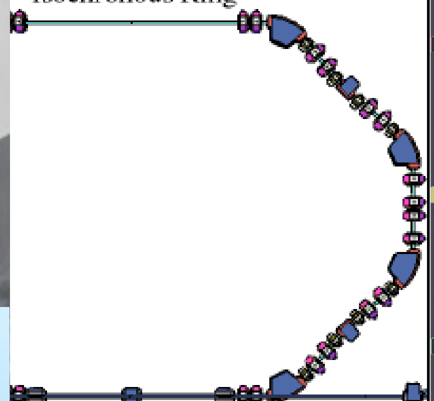
B. B. effect ⇒ **Cathode overheated** ⇒ **Beam current increased**

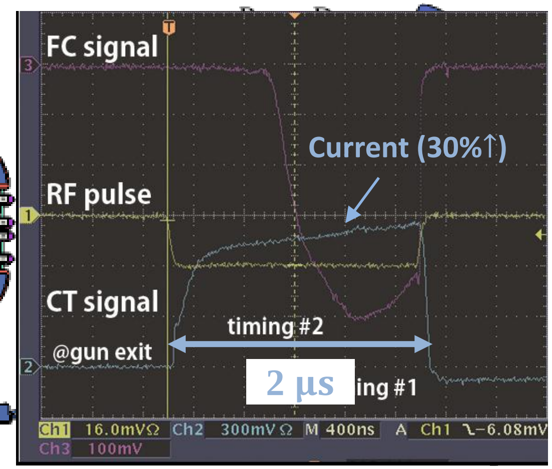
Topics:

1. Evaluation of the B.B. effect on the emission current
2. Suppression of B.B. in different ways



Alpha Magnet

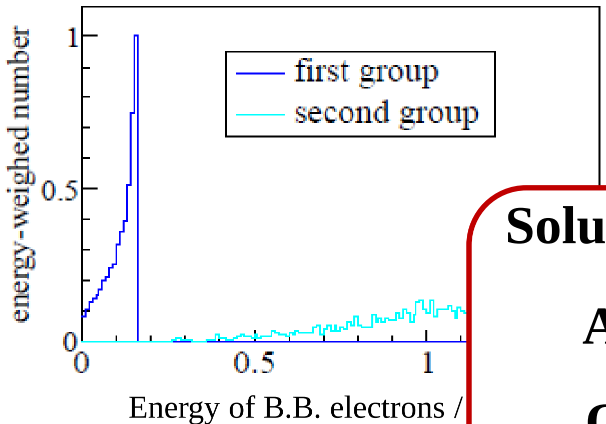




Layout of test-Accelerator as Coherent Terahertz Source (t-ACTS)

Research experience (1)

Evaluation of B.B. effect in a thermionic RF gun



Numerical model

Particle tracking

GPT

Heat transfer

C++

Change of emission current

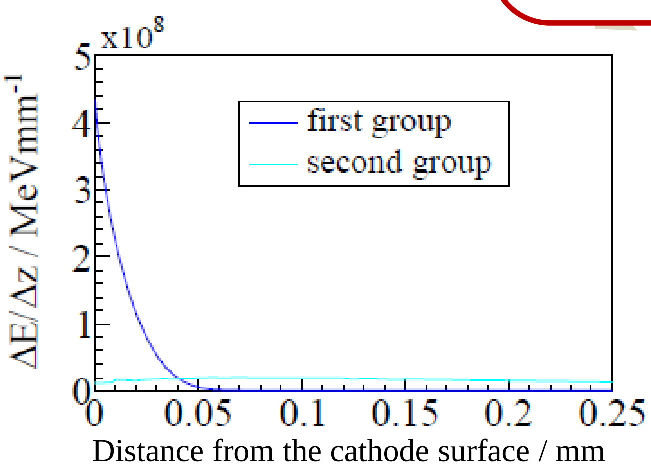
$$J_0 = \lambda A_0 T^2 e^{-\frac{w}{kT}}$$

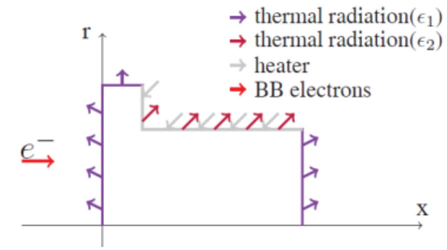
Solutions:

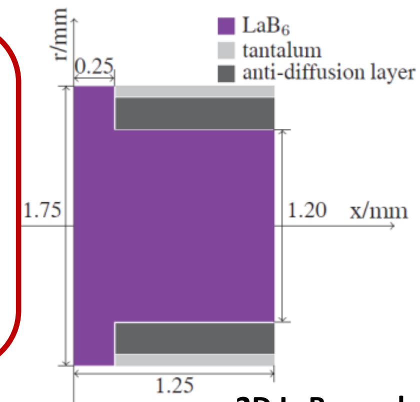
A bending magnet (No)

Optimizing gun parameters

- enlarge the cathode size(Yes)







2D LaB_6 mode

$$\frac{\partial T}{\partial t} = \lambda\left[\frac{\partial^2 T}{\partial x^2} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)\right] + S$$

<u>The low energy electrons are responsible for the overheating of the cathode surface</u>

Research experience (2)

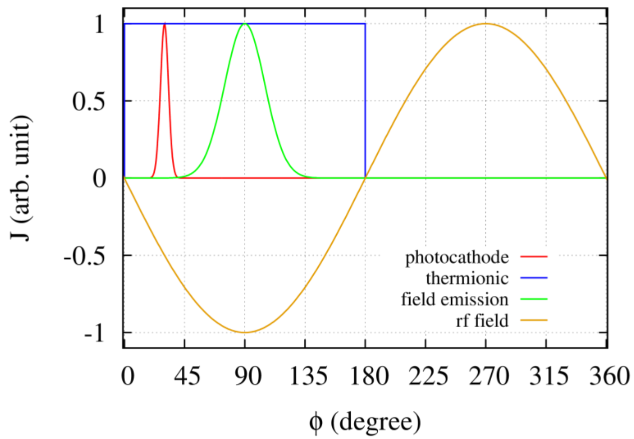
Sep, 2009-Jul, 2015

Theoretical and experimental studies on field emission RF guns

Supervisor: Prof. Chuanxiang Tang

Motivation

To produce ***relatively high brightness*** **and** ***relatively high average current*** electron beam for free-electron lasers



Topics:

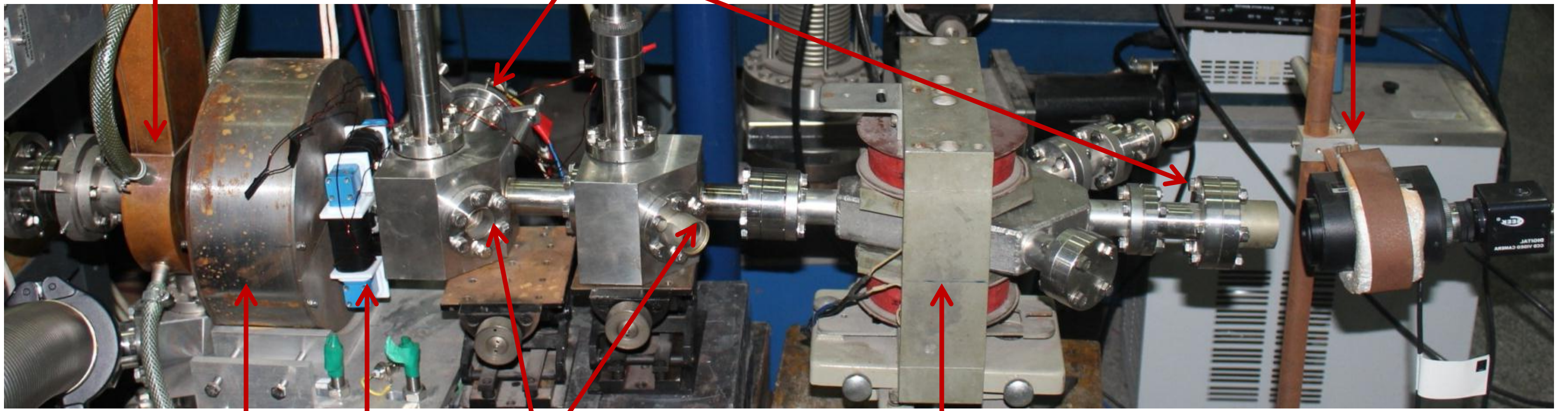
1. Theoretical investigation of FE in RF fields
2. Design of proper RF structures for FE cathodes
3. Design and installation of an RF test stand
4. Characterization of FE current on the test stand

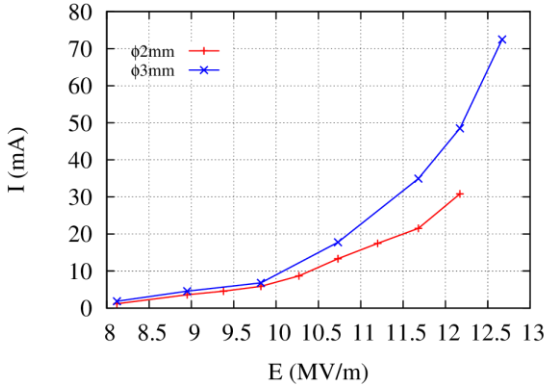
Potential advantages of field emission (FE):

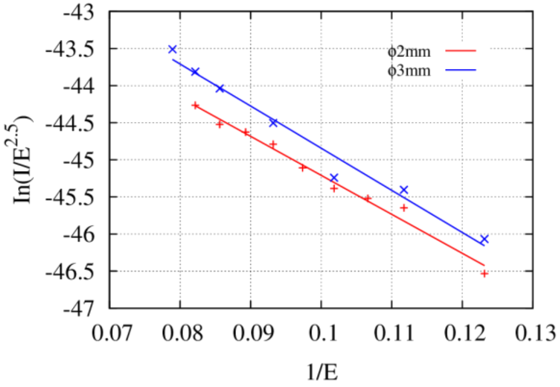
continuous emission; relatively narrow emission phase interval

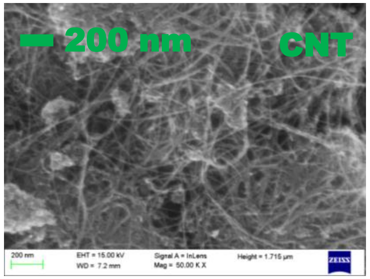
Research experience (2)

Characterization of field emission current in the S-band RF gun









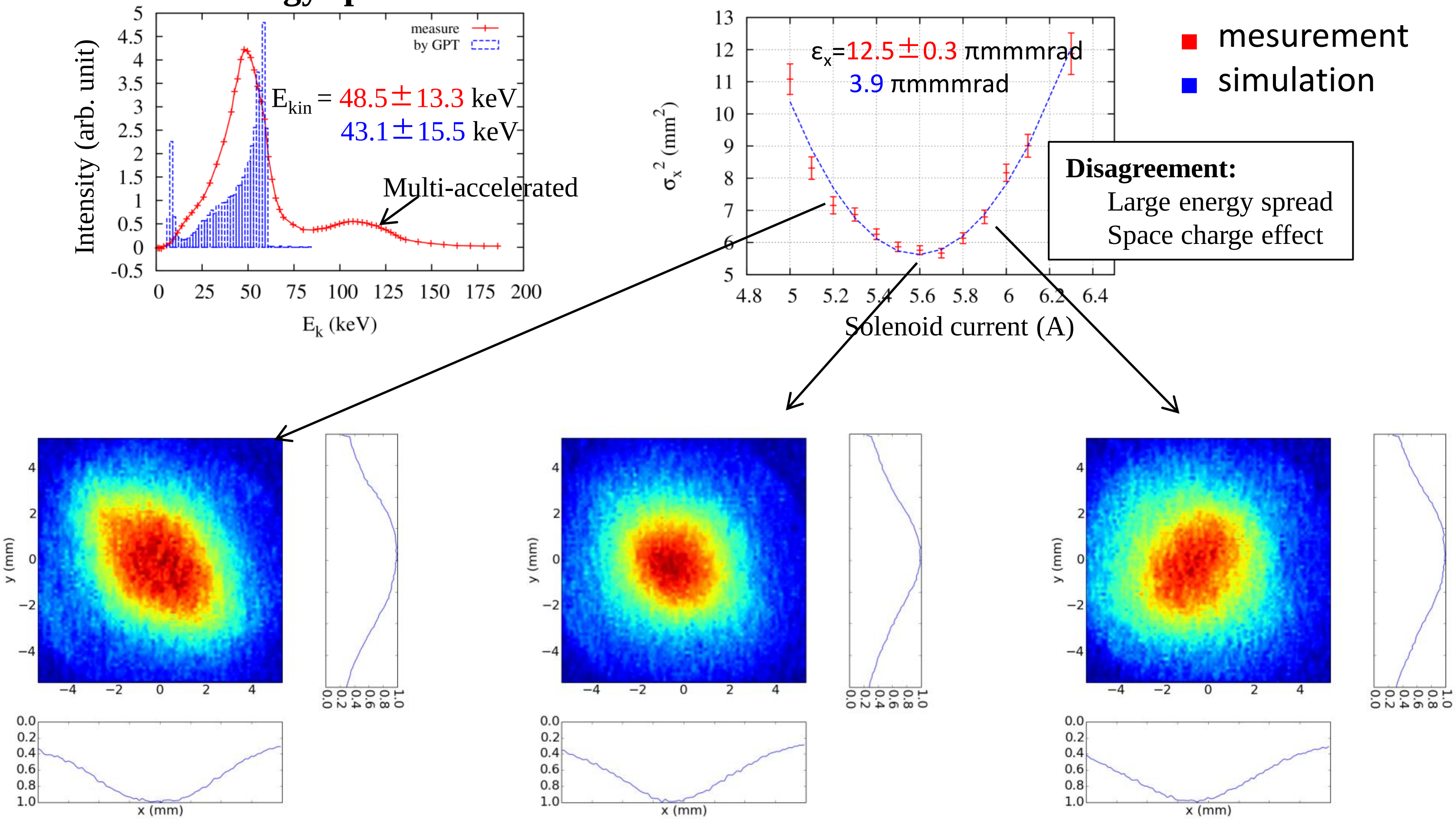
Beam current from *printed carbon nanotubes*

ϕ/mm	2	3
I/mA	30	72
σ_t/ps	~16.7	~15.0

Research experience (2)

Characterization of field emission current in the S-band RF gun

Energy spectrum　　Transverse emittance

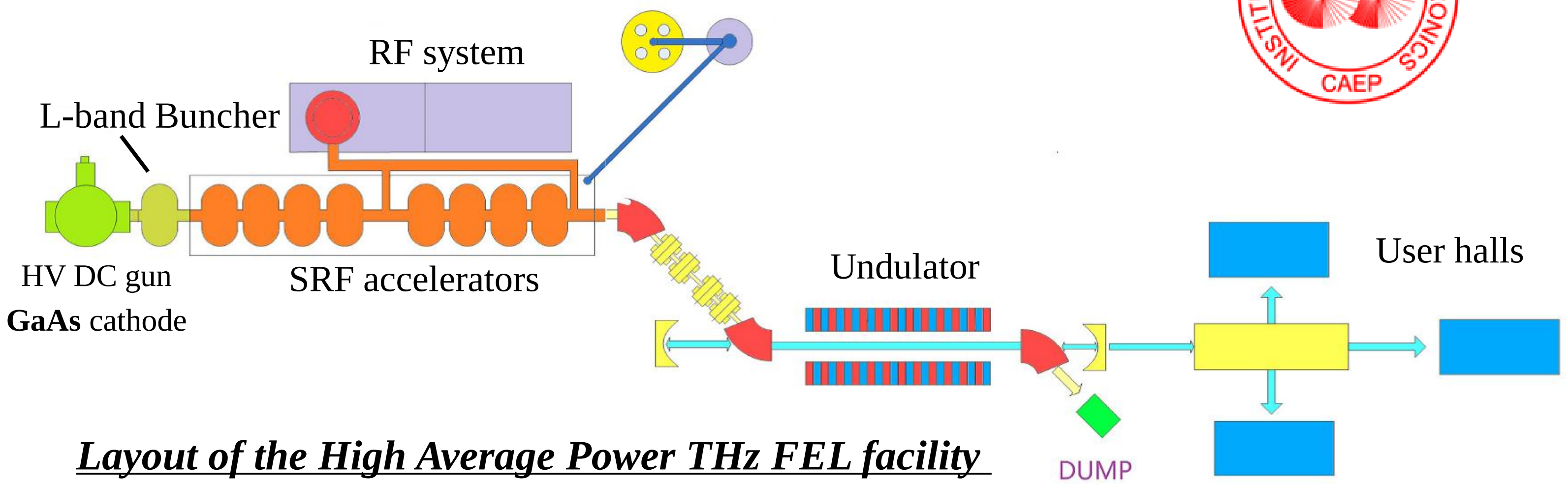


Transverse distribution

Research experience (3)

Jul, 2015-Aug, 2016

Research assistant at IAE, Mianyang, China



<u>Layout of the High Average Power THz FEL facility</u>

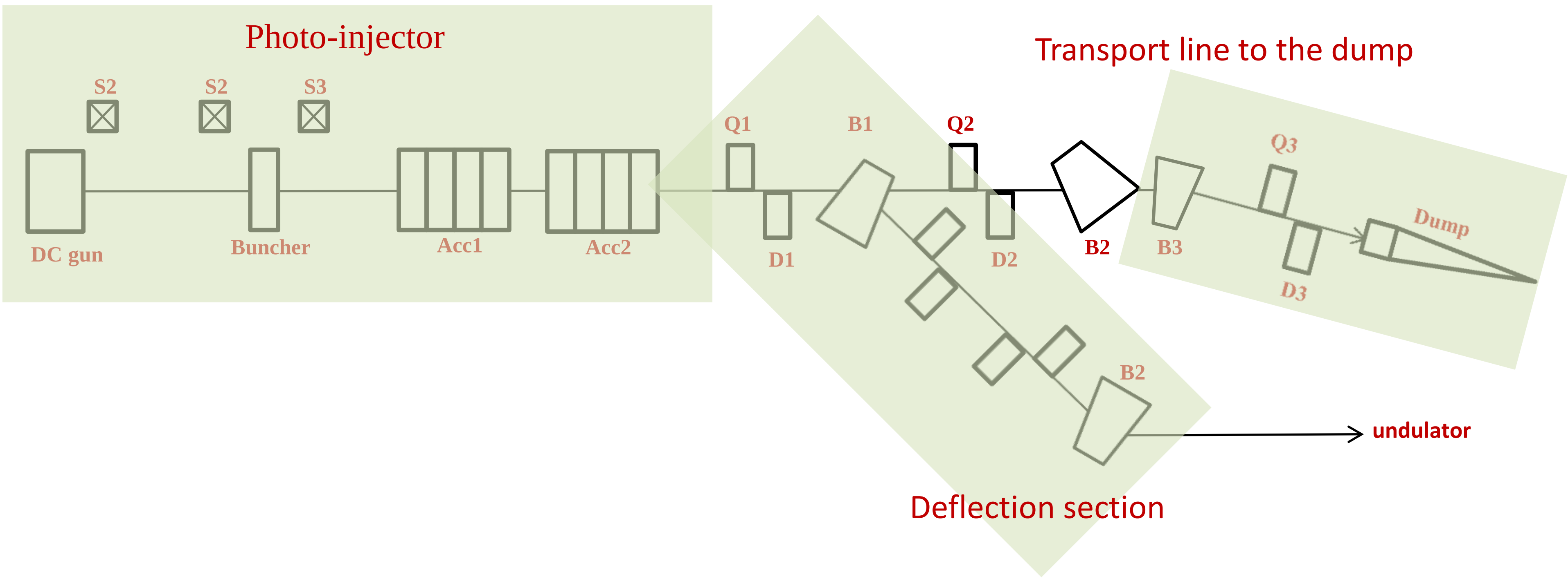
(Rep. rate: 54 MHz; Pulsed or CW mode)

Duties:

1. Optimization of the whole beam line
2. RF related measurements for the buncher
3. Commissioning of the photo-injector (pulsed mode)

Research experience (3)

Optimization of the high average current THz FEL beam line

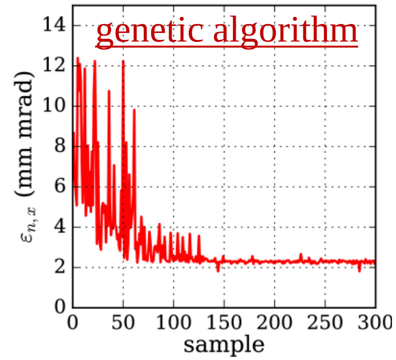


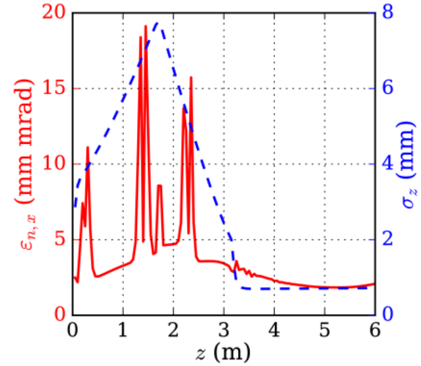
Research experience (3)

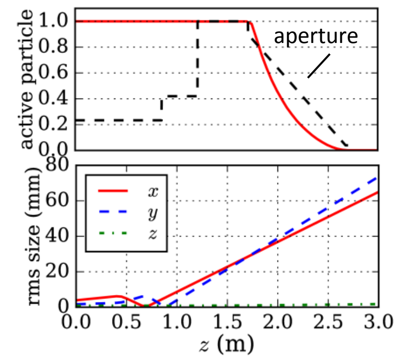
5 variables:
- laser spot size
- 3 solenoids
- buncher field

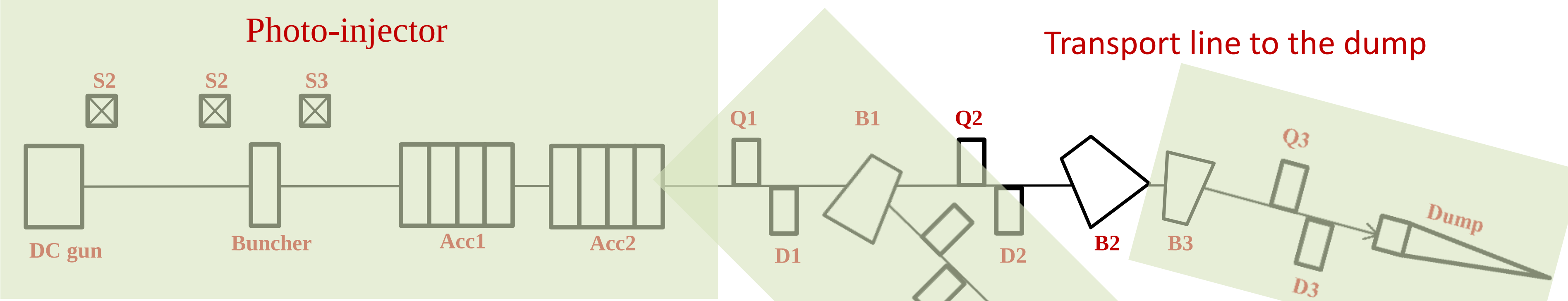
1 constraint:
- bunch length

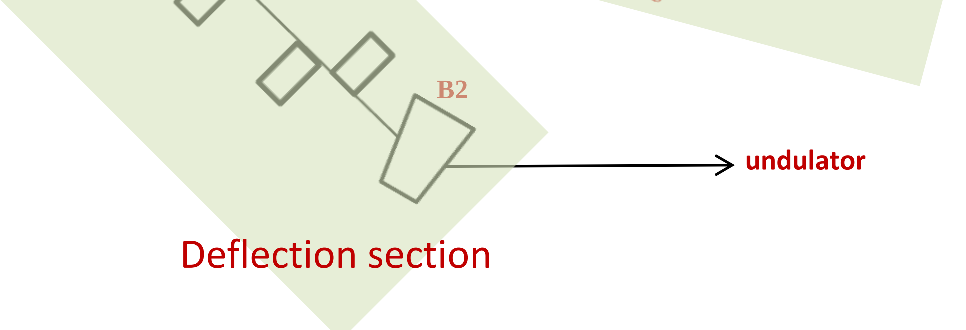
Objective:
- beam emittance

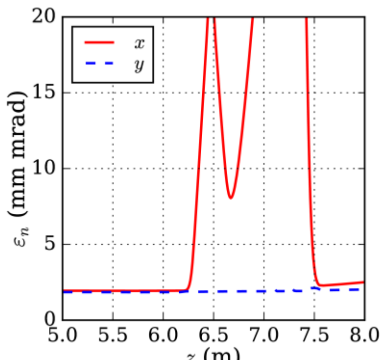


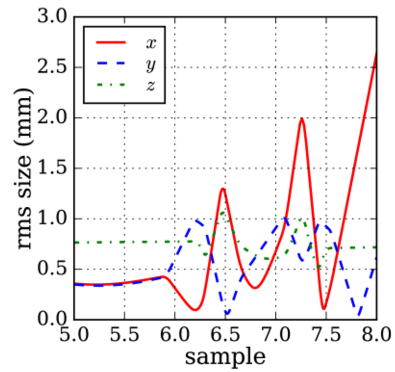












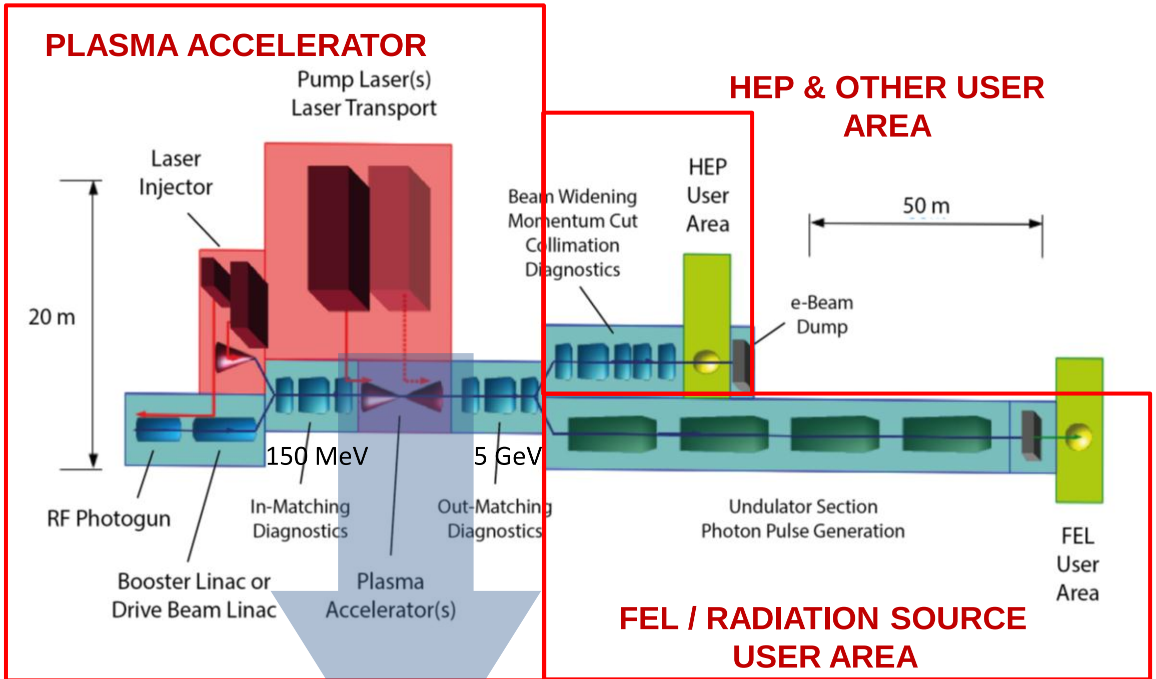
Achromatic design

*Software involved: **Superfish**, **Astra** and **Transport**; GA implemented in **C++***

Research experience (4)

Sep, 2016-Jul, 2018

Postdoctoral position in Beam Dynamics at CEA-Saclay, France



External injection!
Linear or quasi-linear regime!

Duties:

Design of 5 GeV plasma module, ensuring low energy spread during the acceleration and low emittance during the transportation

$$\frac{\sigma_E}{E} < 1\%, \frac{\sigma_{E_S}}{E} < 0.1\%, \varepsilon_n \sim 1 \text{ mmmrad}$$

Research experience (4)

The energy spread is minimized by optimizing the beam loading effect

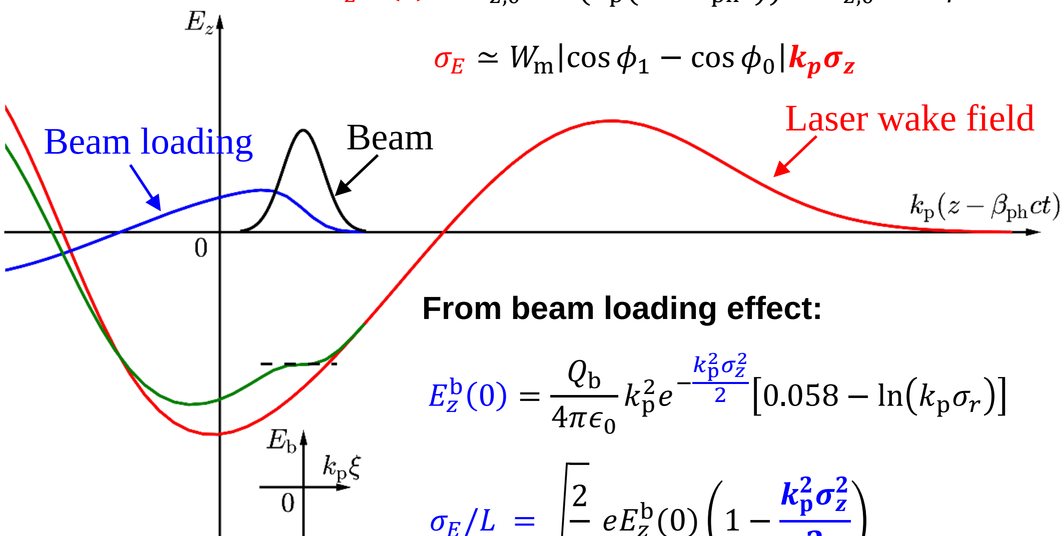
Total energy spread:

$E_{z,0}^{\mathrm{LW}}$: electrical field amplitude
$\beta_{\mathrm{ph}} = v_{\mathrm{ph}}/c$: phase velocity
ϕ_0, ϕ_1: injection and exit phase
$W_{\mathrm{m}} = \frac{eE_{z,0}^{\mathrm{LW}}}{k_{\mathrm{p}}(1-\beta_{\mathrm{ph}})}$: max. energy gain

From plasma wake field:

$$E_z^{\mathrm{LW}}(z) = E_{z,0}^{\mathrm{LW}}\cos\left(k_{\mathrm{p}}(z - v_{\mathrm{ph}}t)\right) = E_{z,0}^{\mathrm{LW}}\cos\phi$$

$$\sigma_E \simeq W_{\mathrm{m}}|\cos\phi_1 - \cos\phi_0|\boldsymbol{k_p\sigma_z}$$



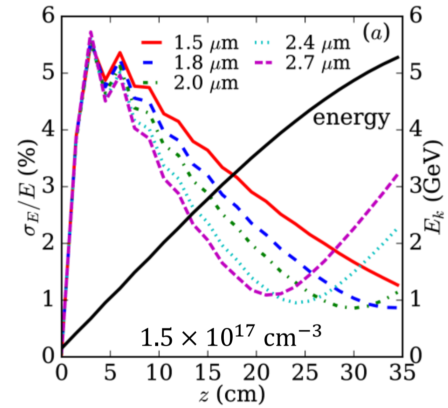
From beam loading effect:

$$E_z^{\mathrm{b}}(0) = \frac{Q_{\mathrm{b}}}{4\pi\epsilon_0}k_{\mathrm{p}}^2 e^{-\frac{k_{\mathrm{p}}^2\sigma_z^2}{2}}\left[0.058 - \ln(k_{\mathrm{p}}\sigma_r)\right]$$

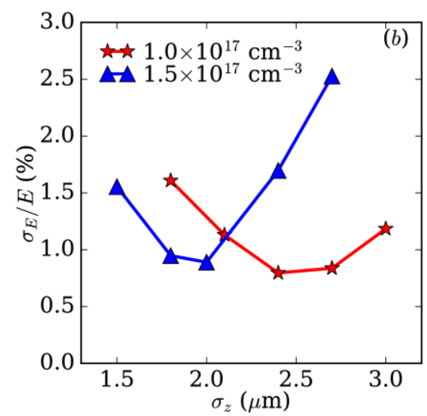
$$\sigma_E/L = \sqrt{\frac{2}{\pi}}\, eE_z^{\mathrm{b}}(0)\left(1 - \frac{\boldsymbol{k_p^2\sigma_z^2}}{\boldsymbol{2}}\right)$$

$E_z^{\mathrm{b}}(0)$: wake field at the bunch center
Q_{b}: bunch charge
σ_r: beam size

$k_{\mathrm{p}}\sigma_z \ll 1, k_{\mathrm{p}}\sigma_r \ll 1$



Energy and spread along acc.



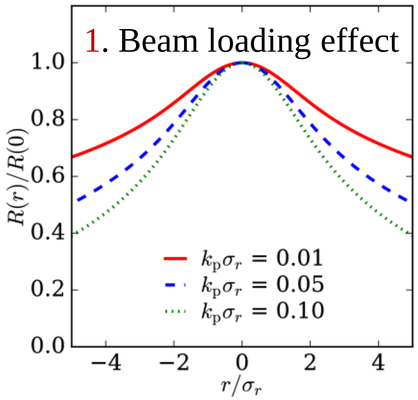
Dependency on bunch length

*Simulation by **Warp***

Research experience (4)

The energy spread is minimized by optimizing the beam loading effect

Slice energy spread:



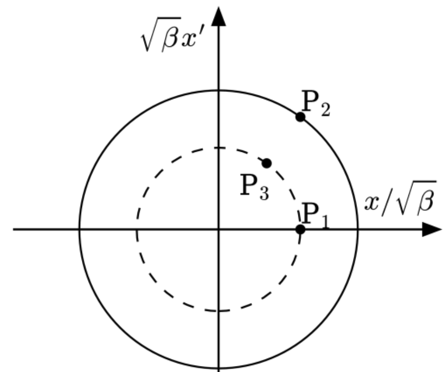
Transverse dependency

Energy gain during one period:

$$\frac{\Delta\gamma}{\gamma} = \frac{eE_{\mathrm{acc}}}{m_e c^2}\frac{2\pi\sigma_x}{\varepsilon_{n,x}} \sim 5\%$$

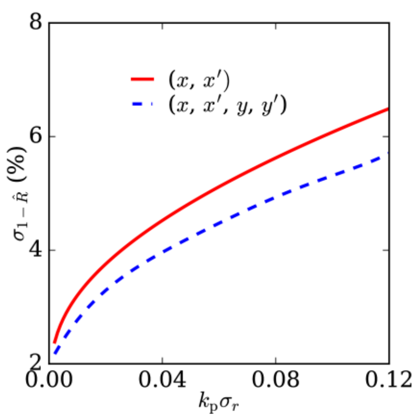
Single particle's motion:

$$x = x_0 \cos\varphi_x + \frac{x_0'}{\sqrt{K}}\sin\varphi_x$$



2. Betatron motion

K: focusing strength; $\varphi_x = \sqrt{K}\,z$; $\alpha_{\mathrm{m}} = 0, \beta_{\mathrm{m}} = 1/\sqrt{K}$ when matched



Its contribution to σ_{E_s}

1+2. Slice energy spread: $$\frac{\sigma_{E_s}}{E} \simeq \frac{E_{z,\mathrm{b}}(\xi)}{\langle E_{\mathrm{acc}}\rangle}\cdot\sigma_{1-\hat{R}}$$

$$\langle[1-\hat{R}]^2\rangle = \int_{-\pi}^{\pi}\int_{-\pi}^{\pi}\int_0^{\infty}\int_0^{\infty}[1-\hat{R}]^2 f(A_x)f(A_y)f(\Delta\varphi)f(\varphi_0)dA_x dA_y d(\Delta\varphi)d\varphi_0,$$

$$\langle 1-\hat{R}\rangle = \int_{-\pi}^{\pi}\int_{-\pi}^{\pi}\int_0^{\infty}\int_0^{\infty}[1-\hat{R}] f(A_x)f(A_y)f(\Delta\varphi)f(\varphi_0)dA_x dA_y d(\Delta\varphi)d\varphi_0,$$

$$\sigma_{1-\hat{R}} = \sqrt{\langle[1-\hat{R}]^2\rangle - \langle 1-\hat{R}\rangle^2}.$$

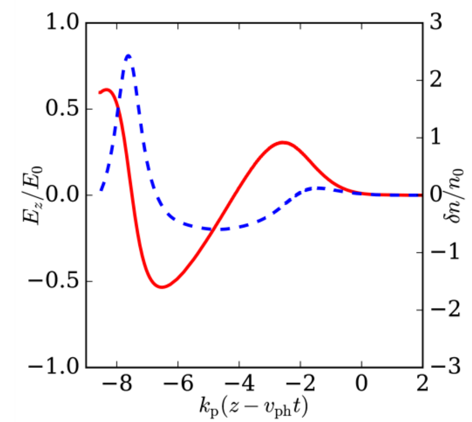
$A_{x,y}$ is the amplitude of oscillation and φ represents the angular distribution in trace space

Research experience (4)

To reduce the slice energy spread:

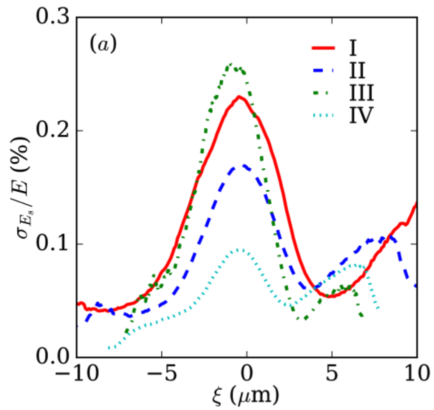
$$\frac{\sigma_{E_s}}{E} \simeq \frac{E_{z,\mathrm{b}}(\xi)}{\langle E_{\mathrm{acc}} \rangle} \cdot \sigma_{1-\hat{R}}$$

1. Changing n_{p} could help increase $\langle E_{\mathrm{acc}} \rangle$, as a result of balancing the wakefield amplitude and acc. phase
2. Increasing a_0 means higher wakefield amplitude (thus higher $\langle E_{\mathrm{acc}} \rangle$) and stronger ponderomotive force (thus lower plasma density seen by the beam which reduces $E_{z,\mathrm{b}}(\xi)$)

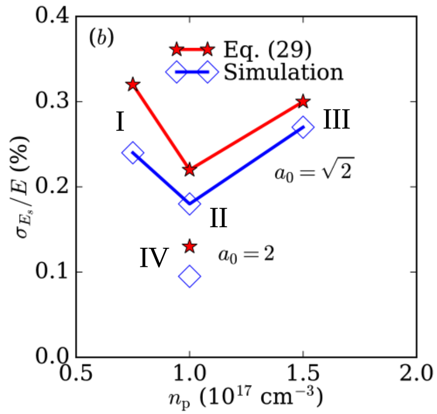


Plasma wake field and density perturbation

Simulations:



Slice energy spread distribution



Slice energy spread at $\xi = 0$

Expectations

- My work will be relevant to the beam dynamics, specific topics still to be decided and your opinions are welcome

- I'm looking forward to learning new things here and working together with you all for the best of our beamline

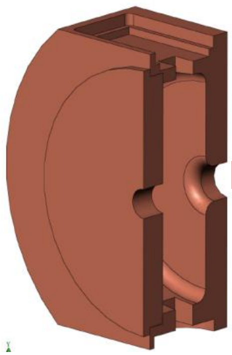
- Very happy to help if needed

Thank you for attention!

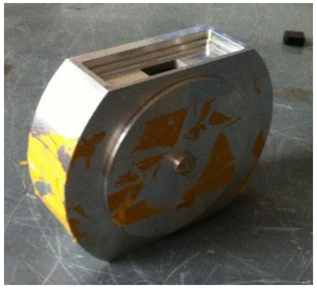
Research experience (2)

Design, test and running of an S-band RF gun for FE

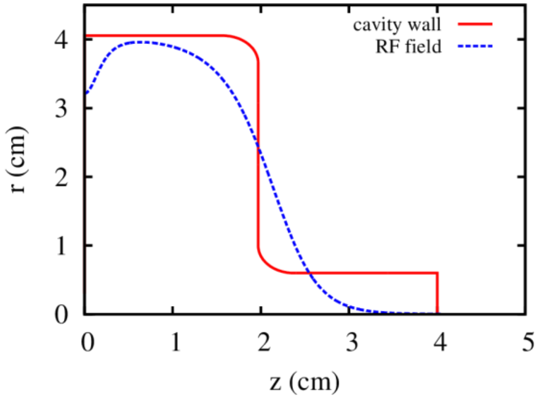
3D model



Aluminium cavity



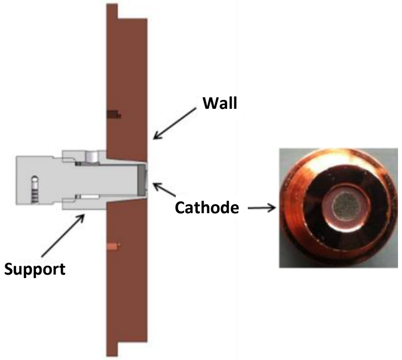
Copper cavity before welding



After conditioning:

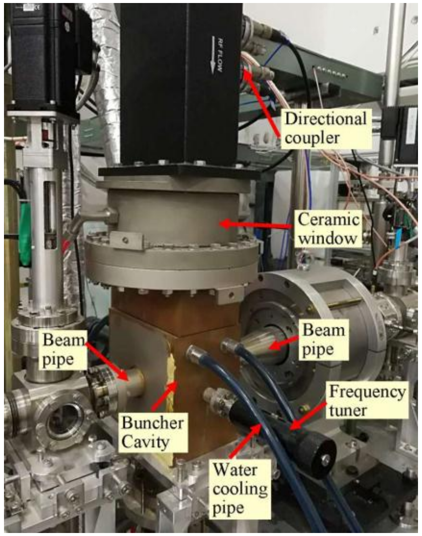
f=2856 MHz, Q0=8500, β=1.86

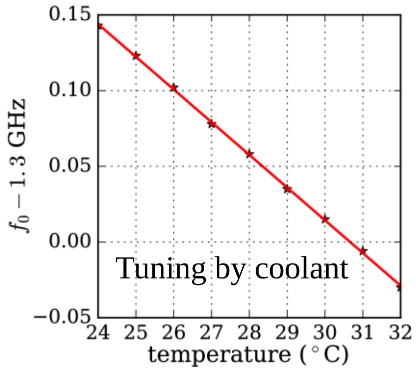
$\boldsymbol{E_{max}}$**~80 MV/m**

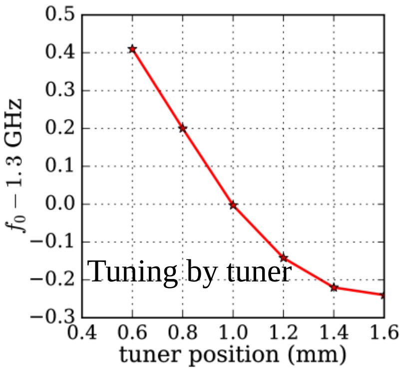


Research experience (3)

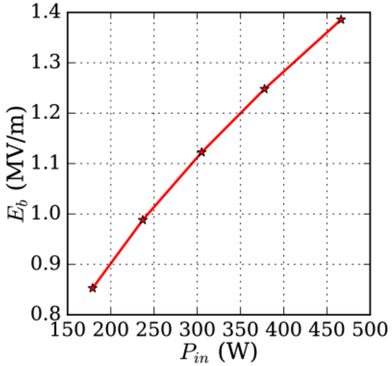
RF related measurements for the L-band buncher at the THz-FEL facility



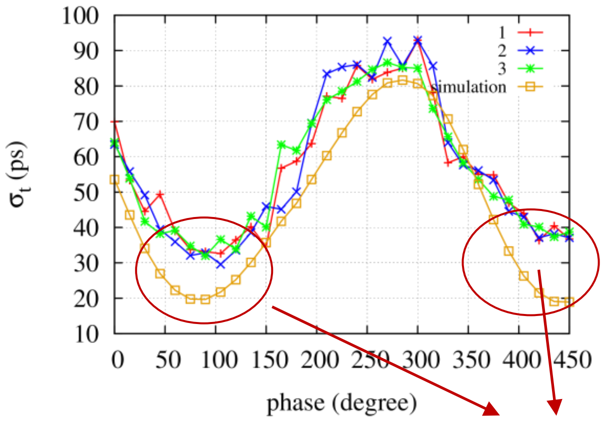




1. Resonant **frequency** on coolant **temperature** and **tuner**



2. Buncher **field** vs. input **power**



3. Bunch length measurement from **Cherenkov radiation** with a **streak camera**

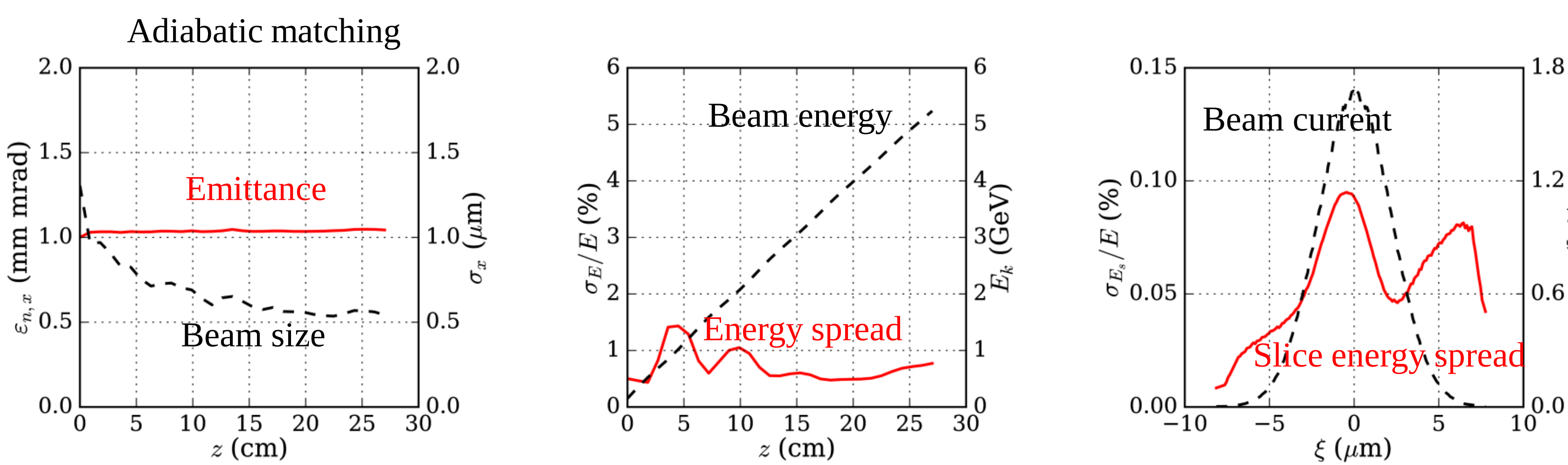
Research experience (4)

Beam parameters required by X-FEL

Beam energy	**5**	**GeV**
Bunch charge	30	pC
Energy spread	<1	%
Slice energy spread	<0.1	%
Beam emittance	1.0	μm

Designed laser-plasma parameters

plasma density	**1×10^{17}**	**cm^{-3}**
plasma length	25	cm
laser strength	2	
laser spot size	50	μm
laser pulse length	132	fs



Optimized beam parameters in the LPAS (Simulated by **Warp**)