PAUL SCHERRER INSTITUT

# Request: Research Support

Villigen PSI, 29.05.2012 Department Head → I. Walthert, OVGA/408 → R. Horisberger

## Title: Electron Fork: noninvasive beam size monitor based on field emitter array

**Applicant:** **Department/Laboratory:**

Soichiro Tsujino SYN/LMN

Hans-Heinrich Braun SwissFEL

**Start date: 1.7.2012** **Project duration (month): 24**

☒ **New proposal** ☐ **Reconsideration or** ☐ **Continuation of No.** ..................

☐ **Financing by subsidies from „third parties“** (dead line: monthly)
- SNF ☐
- KTI ☐
- EU-FP ☐ ☐ EU Project granted
- others: ……………………… ☐ ☐ external funds awarded

☐ incl. ☐ without PSI supplement to …. PhD student salary/ies

☒ **Financing by additional funds from „PSI-Reserve“** (dead line: June 1, 2012)
- CROSS-departmental initiatives (CROSS-Request) ☒

**Comments:** ……………………………………………………………………………………..

**Total budget:** (please fill in **at least** the **grey parts**)

| | **PSI contribution** | | | | **External funds (third funds)** | | **additional funds from PSI-Reserve:** | | **Total** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **own KST** | | **GFA, LOG, construction** | | | | | | | |
| **Consumables** [kCHF] | | kCHF | | kCHF | | kCHF | | kCHF | | kCHF |
| Investments (incl. construction) | | | | | | | | 40 | | 40 |
| Running costs | | | | | | | | 15 | | 15 |
| Research | | | | | | | | | | |
| Decommissioning/ disposal | | | | | | | | | | |
| **Total Consumables** | | | | | | | | | | 55 |
| **Personnel** * | PJ | kCHF | PJ | kCHF | PJ | kCHF | PJ | kCHF | PJ | kCHF |
| PhD student | | | | | | | | | | |
| Postdoc/scientist | | | | | | | 2 | 173 | 2 | 173 |
| Technician/ lab assistant | | | | | | | | | | |
| **Total Personnel** | | | | | | | | **228** | | **228** |

*please consult your 'Bereichs-Drittmittel-Verantwortlichen' or the Technology transfer staff

Date: ……………. Initials department head: ……………………………….

**Abstract:**

Beam size measurement with (sub-)micron resolution in the state of the art particle accelerators is highly demanded and a challenge for beam diagnostics. In free-electron lasers (FELs), established methods such as imaging at optical wavelength from scintillating screens, optical transition radiation, and synchrotron radiation suffer from the coherent radiation, which blurs the transverse electron beam profile. An alternative is wire scanner, as for example used at Linear Coherent Light Source (LCLS) X-ray FEL at Stanford. However it is not capable of single shot measurements and is limited in resolution. For high intensity proton accelerators, e.g. European Spallation Source (ESS), an invasive measurement of this kind may not be preferable because of induced beam losses. Although the laser wire method (the so-called Shintake monitor) [1] is non-invasive and realizes high resolution, it requires extensive instrumentations.

Therefore we propose a novel beam diagnostic based on field emitter array (FEA) technology, which is non-invasive and potentially single-shot capable with relatively simple instrumentations. Beamlets (one-dimensional array of small electron beams), incident perpendicular to the relativistic beam to be measured, are strongly deflected by the electromagnetic field. By analyzing the deflected beamlets pattern, one can obtain the information of the transverse beam profile and beam size. The low current, small diameter beamlets are produced at FEA tips based on a technology developed at LMN. They are accelerated to the order of 10 keV before interacting with the accelerator beam. The deflected beamlets are then imaged on a two-dimensional detector recording the deflection. A suitable detector is available, for example the MediPix technology developed by the MediPix collaboration (including Mittuniversitet Sundsvall and Stockholm University). The effect of the beamlets on the accelerator beam is negligible, thereby an non-invasive and on-line beam quality monitoring may be realized.

We request a post doc position of 2 years to conduct the work for the optimization and the fabrication of the multi-gate field emitter devices, the design of the electron gun and the diagnostic unit with a suitable two-dimensional detector, and the performance test at the injector test facility, aiming at constructing a tool for SwissFEL.

# 1. Research Activities

## 1.1 International Status of the Research Field

Transverse shape of high brightness and short electron pulses is a parameter, among others, that should be monitored to maintain and optimize the performance of accelerators for free electron lasers, colliders, or storage rings, see Ref. [1] and references therein for an overview of the state of the art transverse diagnostic method. One of the typical methods is to scan pinholes or thin wires across the beam and reconstruction of the beam shape from the obtained current values. However, this method is invasive, and it is difficult to characterize small beams in µm-scale. In another method, the image of electromagnetic radiation, which is generated when the electron pulses irradiate a metallic foils inserted on the beam path (transition radiation) is measured and used to evaluate the transverse beam shape of the electron pulses. However, this method is invasive, and it is difficult to characterize femtosecond electron pulses with large populations because of the coherent enhancement due to the high pulse current, which blurs the transverse beam profile.

A non-invasive measurement method is preferred, if not essential, since it enables real time feedback and tuning. A method using Compton scattering of high brightness laser pulses by the electron pulses to be characterized.[1] This is non-invasive but requires scanning of the laser beam, hence not single-shot measurement, and an elaborate gamma-ray measurement setup in the down stream is required. By focusing the laser spot on the beam smaller than the beam size, µm-scale measurement may be possible. The resolution can further reduce to a few hundreds of nanometers by using an interference of the laser pulses, so-called Shintake monitor.[1] However, it is difficult to vary the measurement resolution from tens of µm down to sub-µm scale without significant change of the optics of the probe laser beam.

In electron storage rings, the beam size is in general measured utilizing the synchrotron radiation and pinhole. Although an analysis based on point-spread function allows us to resolve beam sizes below the diffraction limit, the method is in principle limited.

## 1.2 Status of Research at PSI: Field emission cathode R&D as a SwissFEL cathode

In the past years, we studied a possible way to improve the electron beam quality of electron gun, in particular, the use of a field emission cathode as a possible alternative way to surmount the electron beam brightness of photocathode by more than a factor of 2, Refs. [3-19]. The requirements for SwissFEL cathodes are, [20]

1) Generation of 200 pC or 10 pC for low-charge mode, with ~10 ps pulse duration,
2) Transverse beam emittance below ~0.4 mm-mrad, and
3) Withstand the high acceleration electric field (tens of MV/m and higher).

The unavailability of such field emission cathodes has demanded investigation of basic physics and break through. During past years, we have proposed [8] and demonstrated [9] a new fabrication method of a metallic nano-tip array cathode supported on a metallic substrate. Main achievements we demonstrated with these cathodes are following,

1. Up to ~5 pC charge generation by 50 fs near-infrared laser irradiation of single-gate devices with the tip quantum efficiency in the order of (0.1-1)%, [10, 11, 16, 18]
2. Collimation of array emitter beams and reduction of the beam divergence angle by factor (5-10), with the minimum angle below 1°, with stacked-double-gate devices with on-chip beam collimation electrode for individual tips, [12, 15, 19]
3. Stable operation of single-gate devices under pulsed acceleration field up to 30 MV/m and subsequent acceleration of the beam up to 5 MeV and picosecond electrical switching of field emission beam in the high acceleration electric field, [13, 14, 17]
4. Finding of a method to control the distribution of field emitter sharpness in-situ, to improve the emission beam uniformity. [17]

The realization of the high-beam-brightness field emission cathode with the performance theoretically predicted in Refs. [3, 4, 5, 21] requires further increase of the charge generation efficiency and development of fabrication technology for the double-gate devices with 10-100 k-tips. The latter is under way, cf. Fig. 7, within a currently running FoKo-funded PhD project.[19] The first requirement, further increase of the bunch charge, calls for more detailed analysis and involves several scientific questions as described in our recent SNSF project proposal submitted on April 2012 as the follow up of the currently running SNSF PhD project which will finish by the end of 2012.[18]

### 1.3 Presentation of the Research Goals and the Research Plan

Here we propose a method to characterize the transverse size of short high brightness particle bunches by using a low energy electron beamlets as the probe. In this method, we detect the deflection of the probe electron pulse by the high-energy bunch, when the probe pulse beam is incident perpendicularly to the bunch propagation direction, Fig. 1 (left). This is a non-invasive method, which is in principle capable to make the measurement by a single-probe-pulse. There is no report of such method in literature.

In the following, we describe the basic scheme and principle of the method based on preliminary simulation for SwissFEL electron bunches as an example, the applicability of realistic electron beams, and the basic strategy to develop such electron source based on the PSI field emission cathode.

### 1.3.1 Goal of the research

The goal is to elucidate the possibility and the quantitative requirements to apply the deflection of field emission beamlets to detect the transverse properties of the relativistic high-brightness particle beams used for X-ray free electron lasers, state-of-the-art synchrotron radiation sources, future linear colliders and spallation sources.

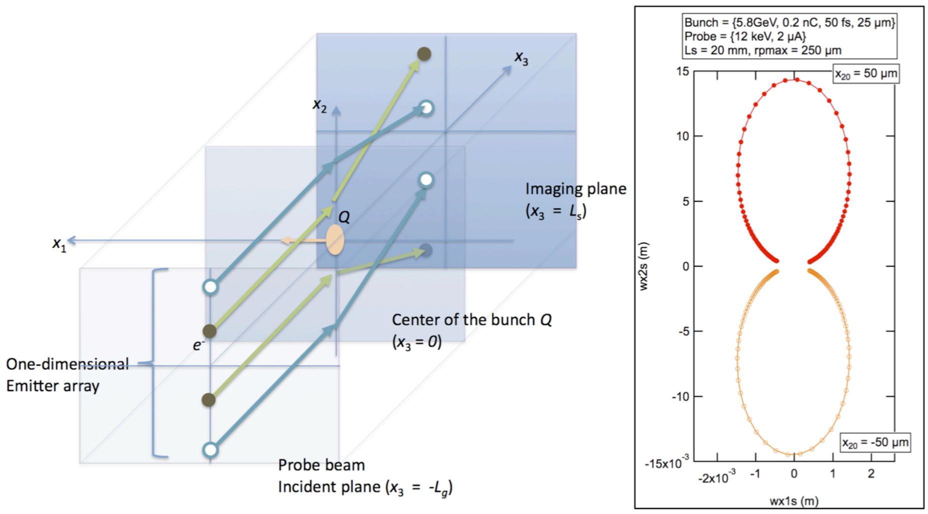


Figure 1 (left) Deflection of low-energy electron beamlet by a femtosecond relativistic electron bunch. (right) Deflection orbit of probe electron beamlet emitted from $x_{20}$ = ±50 μm and $x_3$ = -10 mm by the bunch, detected by a two-dimensional electron detector located at $x_3$ = 20 mm.

### 1.3.2 Transverse beam size measurement of SwissFEL electron bunches by low-energy beamlets

In Figure 1, we display the basic principle of the proposed method. As shown in Fig. 1 (left), when the high brightness electron bunch $Q$ propagates along the $x_1$ axis in the positive $x_1$ direction, the probe electron pulses are generated from the source array on the plane at $x_3$ = - $L_g$ and propagates in the $x_3$ direction. The probe pulse generated from a source located at a positive $x_2$ coordinate is deflected by the electric field of the bunch to the positive $x_2$ direction. When the probe pulse source is located at a negative $x_2$ coordinate, the deflection is to the negative $x_2$ direction. In addition, the bunch also deflects the probe electrons in the $x_1$ direction by its magnetic field. When the $x_3$ coordinate of the probe electron is negative at the time the bunch passes through, the magnetic force is directed to the negative $x_1$ direction, but it’s positive when the probe electron is at a $x_3$ positive position. As a result, when a probe pulse synchronized to the high-energy bunch is detected by a two-dimensional detector located at $x_3 = L_s$ (>0), the deflected orbit of the pulse exhibits an elliptical shape.

In Fig. 1 (right), we show an example of the deflected low energy probe electron pulses by a SwissFEL electron bunch, the beam energy of 5.8 GeV, the bunch charge of 0.2 nC, and the bunch duration of 100 fs with the circular transverse bunch shape (the radius $R_b$ of 25 μm). Assuming probe electron pulses with the beam energy of 12 keV, the pulse current amplitude of 2 μA, and the sources (at $x_3$ = -10 mm) located at $x_2$ of ±50 μm, as a result of the deflection, the probe electrons form elliptical on the detector screen at $L_s$ of 20 mm, as shown in Fig. 1 (right). This was obtained by numerically integrating the equation of the motion. The deflection of the probe pulse in the order of 10 mm in the $x_2$ direction and 1 mm in the $x_3$ direction are expected. The two dimensional detection of such deflection orbits with single-electron sensitivity should be possible by various methods, including the MediPix detector.

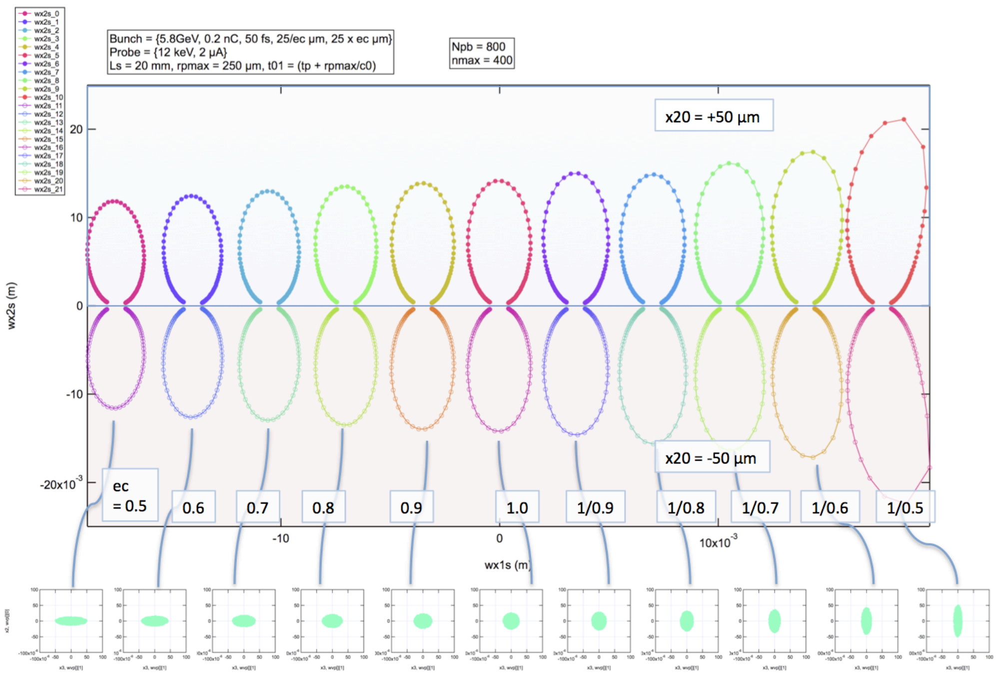


Fig.2 Deflection of probe electron pulses by SwissFEL bunches with various transverse beam size (different aspect ratio).

More importantly, these deflection orbits are also sensitive to the transverse shape of the SwissFEL electron bunch. Firstly, in Fig. 2, we demonstrate the impact of the aspect ratio of the transverse bunch shape on the deflection. Assuming SwissFEL bunches with elliptical shape with the $x_2$ radius $R_{b2}$ equal to $R_b \times \eta$, and the $x_3$ radius $R_{b3}$ equal to $R_b/\eta$ ($R_b$ = 25 μm), with $\eta$ varied from 0.5 to 2, Fig. 2 shows that, when $R_{b2}$ is increased, the deflection orbit of the probe pulse is further elongated in the $x_2$ direction; it increased from 10 mm to ~20 mm when $R_{b2}$ was changed from 12.5 µm to 50 µm. This is mainly the consequence of the increased bunch electric field.

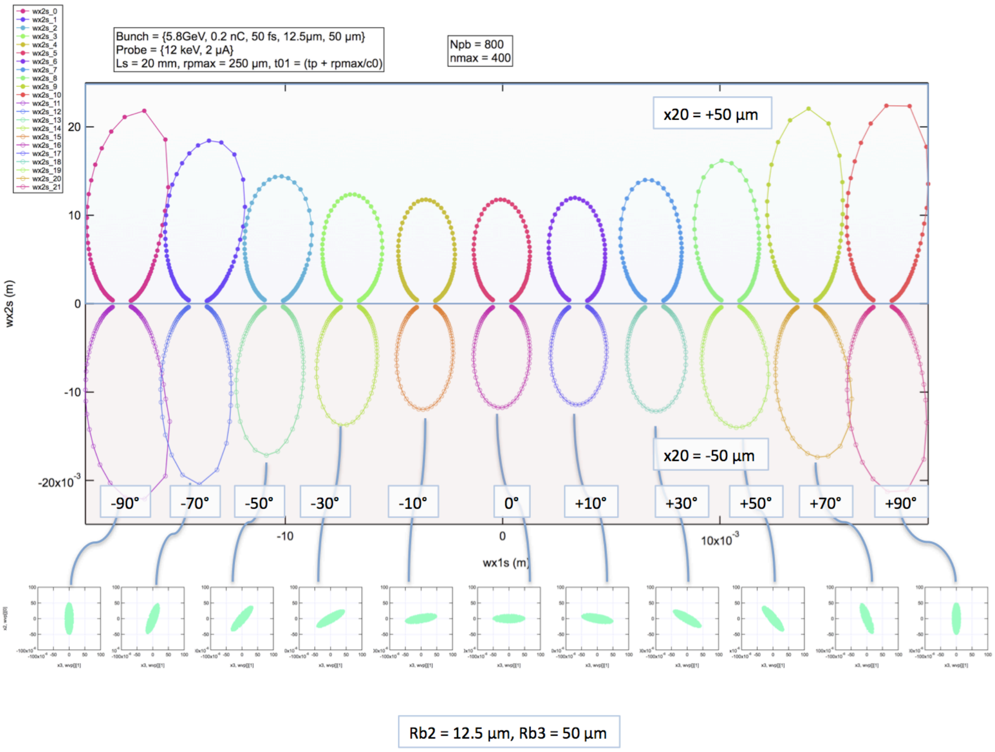


Fig.3 Deflection of probe electron pulses by SwissFEL bunches with various transverse beam size (asymmetric shape with rotation).

Secondly, in Fig. 3, we demonstrate the impact of the rotation of asymmetric transverse shape of the SwissFEL bunch. Here we assumed that the SwissFEL bunch has $R_{b2}$ of 12.5 µm and $R_{b2}$ of 50 µm, rotated from -90° to 90°. Here we observe two characteristics, i) the elongation/shrink of the deflection orbit in the $x_2$ direction with the increase/decrease of the projected bunch size in the $x_2$ direction, and ii) the tilt of the deflection orbit. i) is similar to the observation in the Fig. 2. ii) is the impact of the asymmetry; When the longer radius of the elliptic shape bunch is in the first (and the third) quadrant as in the case of -10° to -70° rotation angles in Fig.3, the deflection orbit of the probe pulse generated from the source at $x_{20}$ = +50 µm is slightly rotated in the clock-wise direction, whereas the deflection orbit of the probe pulse generated from the source at $x_{20}$ = -50 µm is rotated in the counter-clock-wise direction.

The tilt is due to the asymmetry of the interaction time of the magnetic component of the Lorentz force, which is originated by the asymmetric and rotated shape of the transverse bunch profile. The simulation shown in Fig. 3 indicates that the deflection orbits of the probe beam by the elliptic bunch with the rotation angle of +θ and –θ are approximately symmetric by 180° rotation. This appears to be because the electric force and the magnetic force affects the deflection of the probe beam in a correlated way; the tilt of the deflection orbit is also relate to the propagation direction of the bunch (either $+x_1$ or $-x_1$ direction).

Comparison of the deflection orbit of the probe beam in Figure 2 with $\eta$ of ~0.7 (the bunch shape is up-and-down symmetric) and that in Figure 3 with $\vartheta$ of ~30° (not up-and-down symmetric but with similar projected thickness in $x_2$ direction as $\eta$ ~0.7 case in Fig. 2) reveals that the probe beam deflection is sensitive not only to the projected thickness of the bunch in $x_2$ direction but indeed also to the asymmetry and the rotation of it. Care should be taken in the case of $|\vartheta|$ ~90°; the deflection orbit is also tilted in this case, however, the comparison of the tilt between the two probe pulse with equal $|x_{20}|$ but different sign of $x_{20}$ makes the sign of those tilt different. Therefore one can distinguish such case with the rotated asymmetric bunch.

### 1.3.3 Impact of finite beam divergence of the probe beam

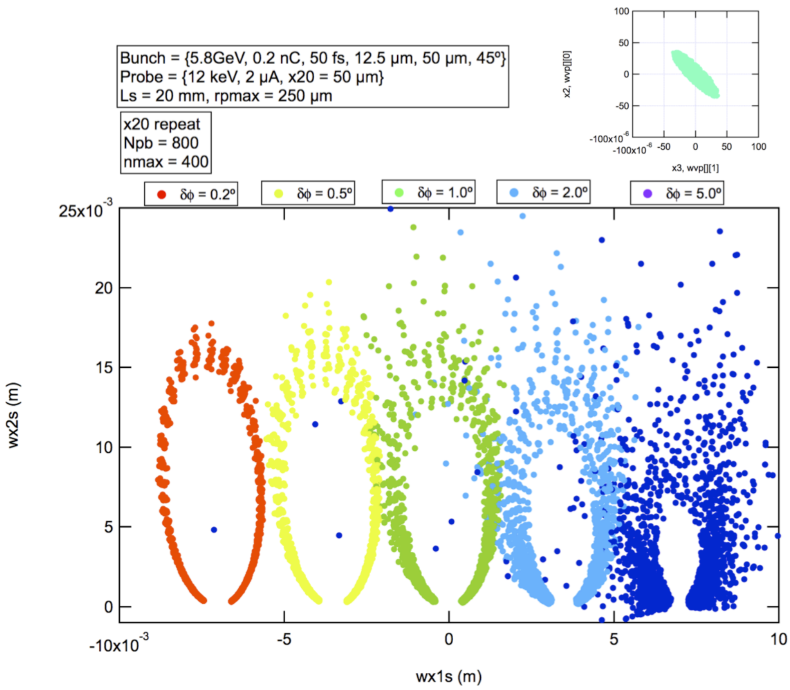


Fig.4 Deflection of probe electron pulses with finite angular spread by FEL bunches

In Figures 2 and 3, we assumed probe electron pulses with pencil-like shape and one-dimensional array of those. Since any actual probe beam will have finite transverse velocity spread $\delta v$, we simulated its effect for an FEL bunch with asymmetric transverse shape with 45 degree rotation for five different cases with $\delta v$ given by $v_0 \sqrt{\langle \sin(\phi)^2 \rangle} \approx v_0\, \delta\phi$, with $\delta\phi$ of 0.2°, 0.5°, 1°, 2°, and 5°, where $v_0$ is the velocity of an electron with ~100 eV beam energy (as stated below this form assumes a field electron emission beam extracted by ~100 V extraction potential and collimated by the on-chip focusing gate lens). Fig. 4 shows the result. For each $\delta\phi$, total of 20 probe pulse deflection were calculated and displayed together. Fig. 6 shows that probe electron pulses with the angular spread ($\delta\phi$) below ~1° can approximately reproduce the previous simulations with pencil beam by averaging the 20 probe pulse deflection orbits. When $\delta\phi$ is below ~0.2°, single-shot measurement appears to be possible.

### 1.3.4 Transverse beam size measurement by low-energy beamlets for other relativistic particle bunches

We also looked into the impact of the SwissFEL injector on the deflection of the low-energy beamlet. These are important not only by themselves but also as a possibility to test the performance of the proposed method at other accelerators. For proton accelerators, the here proposed method may similarly be useful for single-shot diagnostics.

Figures 5 shows the results of the simulation for the probe beam deflection by the high-energy bunch of the SwissFEL injector test facility (250 MeV beam, 0.2 nC charge, 200 fs pulse duration, and the transverse bunch radius of 100 μm). Similar probe beam, the beam energy of 12 keV, the current amplitude of 1 μA, was assumed. The probe beam position in the $x_2$ direction of $x_{20}$ = ±200 μm was assumed here because of the larger radius of the Injector bunch. As a result, the spread of the probe beam deflection is about a factor of 4 smaller than Figs. 2 and 3. However, the effect of the asymmetry and rotation of the bunch (Fig.4) is qualitatively same as the simulation result for the FEL bunch, Fig. 3.

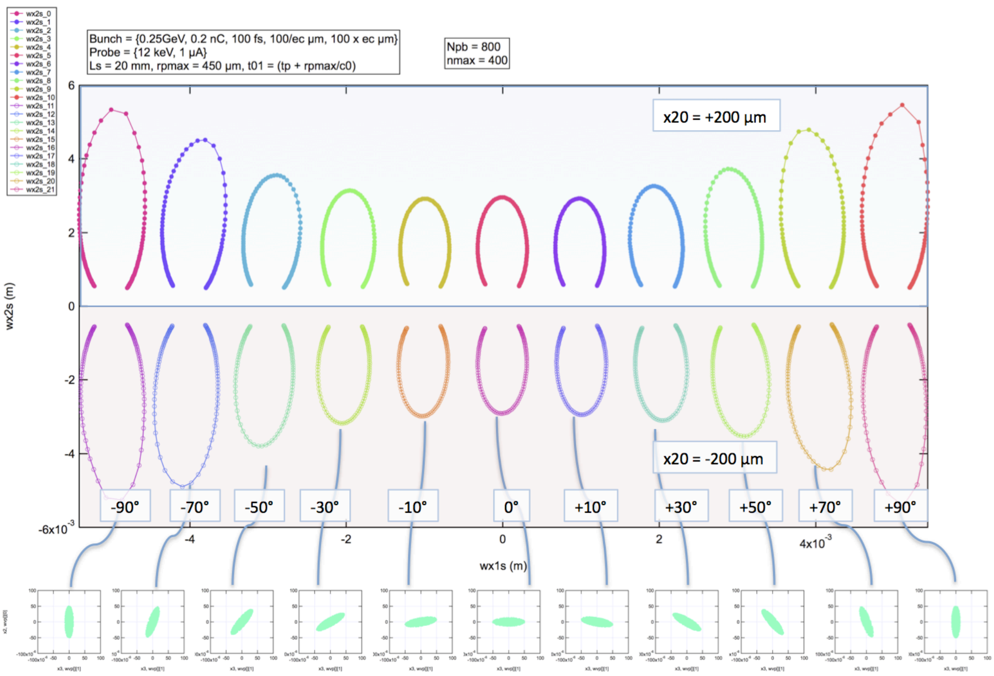


Fig.5 Deflection of probe electron pulses by Injector bunches with various transverse beam size (different aspect ratio).

### 1.3.5 PSI field emitter array cathodes for the transverse beam size measurement

As a source to generate such probe electron pulses, the field emission cathode prepared by micro- and nanofabrication method is most promising. The intrinsic high beam brightness of the field emission electron beam generated from a single-tip field emitters is well known for atomic resolution electron microscopy applications.[23] The high brightness of the field emission electron beam is obtained as the combination of the high current density of field emission process and the very small virtual cathode size (a few nanometers or below). When an array of high brightness beam is required, such as the measurement of the transverse beam size of FEL beam, a field emitter array cathode with integrated multiple gate electrode, in particular, an electron extraction gate (G1) and a electron focusing/collimation gate (G2), is required. As a field emitter array cathode, Spindt-type devices with single gate (G1) electrode, invented in 1970's are the most famous,[24] which exhibited the highest array current density over 1 kA/cm$^2$.[25] One other typical way to fabricate field emitter arrays is so-called transfer mold method developed by NRL and Toshiba.[26]

The PSI field emitter array is fabricated by a modified version of the transfer mold method to control the apex radius of curvature in 5-10 nm scale [8] and have on chip stacked double-gate electrodes.[12, 15, 19] High acceleration electric field compatibility, generation of ultrafast charge generation by near infrared laser induced field emission, and picosecond electrical gating has been demonstrated using PSI field emitter array with single-gate type as described in §1.2.

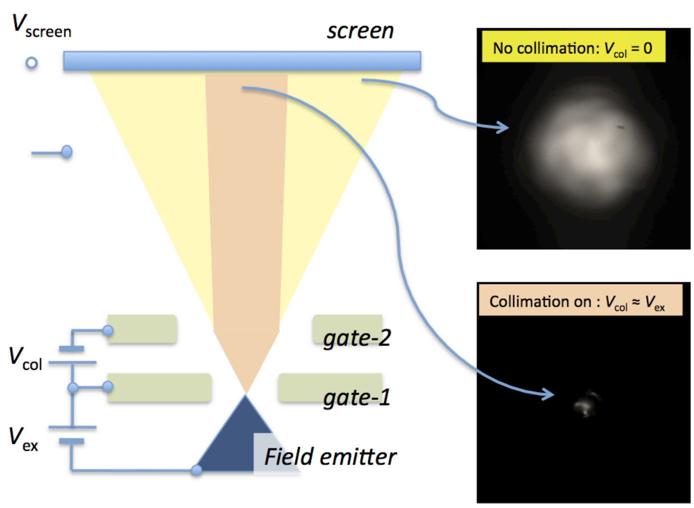


Fig.6 Phosphor screen detection of double-gate field emission cathode performance, showing un-collimated (no G2-potential) and collimated (VG2 ~ VG1) conditions. The cathode is a 10k-tip double-gate molybdenum field emitter array, operated at 100 nA emission current with $V_{ex}$ of 60 V. The evaluated current density enhancement was ~100. Screen was biased at 3 kV.

Because of the curved tip apex, the transverse beam spread of a single field emitter is large, 20-30° half width, but correlated with the distance from the tip axes. Therefore, an optimized G2 can substantially reduce the angle by a factor 10 or more as demonstrated in Ref. [15] and Fig. 6. In this particular experiment shown in Fig. 6 with finite low electron current operation, the enhancement of the current density was a factor of ~100 since the loss of the emission current by the collimation potential was small (~1/3).

The generation of the collimated electron beam is achieved by applying a negative potential to G2 with respect to G1 with the amount comparable to the electron extraction potential applied between G1 and the emitter. Since the negative collimation/focusing potential can decrease the electric field $F_{apx}$ at the field emitter apex, the challenge has been to minimize this $F_{apx}$ reduction. In PSI double-gate structure, this was achieved by increasing the G2 aperture diameter, about a factor of 3 larger than the G1 aperture diameter. This reduced the influence of the collimation/focusing potential on $F_{apx}$ by more than a factor of 3, which is significant, since the field emission current can vary nearly 5 orders of magnitude with a factor of 2 variation of $F_{apx}$. Prof. Mimura's group of Shizuoka University, Japan, has also demonstrated similarly efficient collimation of field emission beam in multiple-gate electrode devices. [27] Their device, based on the geometrical shading of G2 from G1 in a volcano-shape structure design, have a large protrusion of the emitter structure, thus our stacked gate structure is more appropriate for applications that require high acceleration electric field, although their recent demonstration of focusing in triple gate structure, Fig. 7 (right) indicates the potential of further optimization of the device performances of these devices. [28] Our preliminary simulation of field emission beam from double-gate and triple gate devices indicates that similar collimation/focusing characteristics can be achieved by PSI FEAs with stacked gate structures, as shown in FIG. 8.

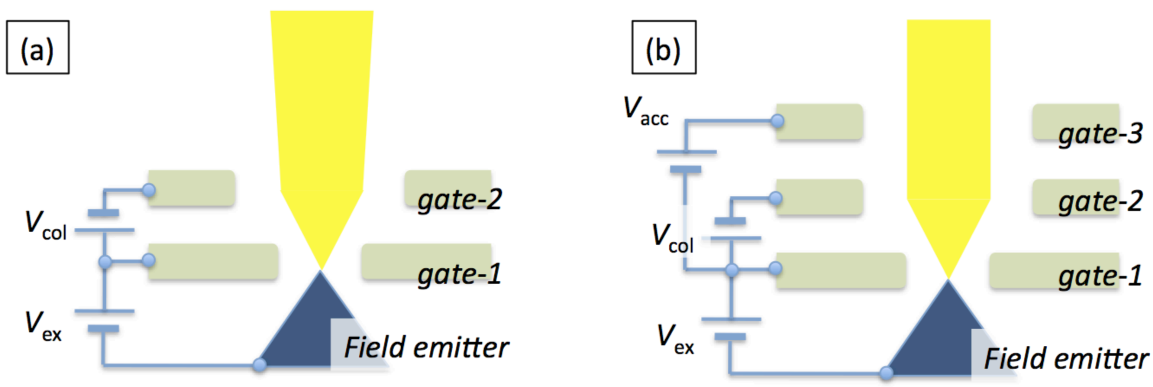


Fig. 7 Schematic comparison of (a) double-gate and (b) triple-gate field emission cathode.

Nevertheless, there is no systematic study including the detailed analysis of the ultimate device performance. In the case of etched-wire needle-shaped field emitters, the beam characteristics (the beam brightness, the beam coherence or the virtual cathode size) have been extensively studied theoretically and experimentally, which demonstrated and established the superiority of field emission cathode for applications that require high-beam brightness (but not necessarily require high current) such as high-resolution electron microscopy (cf. [22]). The advantage of the nano-fabricated field emitter array cathode for applications such as the here proposed special diagnostics is apparent as demonstrated in the earlier part of this proposal, once those are equipped with proper gate electrodes. However, due to the lack of satisfactory double-gate FEAs, that are capable to collimate/focus the individual electron beamlet with minimum loss of the beam current, in the literature, there is no systematic comparison of theory with, the analysis of aberration and as a result of the potential profile created by the gate electrode as well as the image potential at the gate electrode created by the field emission electron beam itself. It is therefore very important to conduct such research for PSI FEAs, a double-gate device as well as the triple-gate version of those. It is also crucially important to assume a realistic acceleration electric field in the order of 1-5 MV/m or higher, which PSI FEAs are compatible with, because according to the recent experiment and numerical simulation, high acceleration electric field can allow increasing the beam collimation potential to give additional factor of 2-10 reduction of the beam divergence angle.

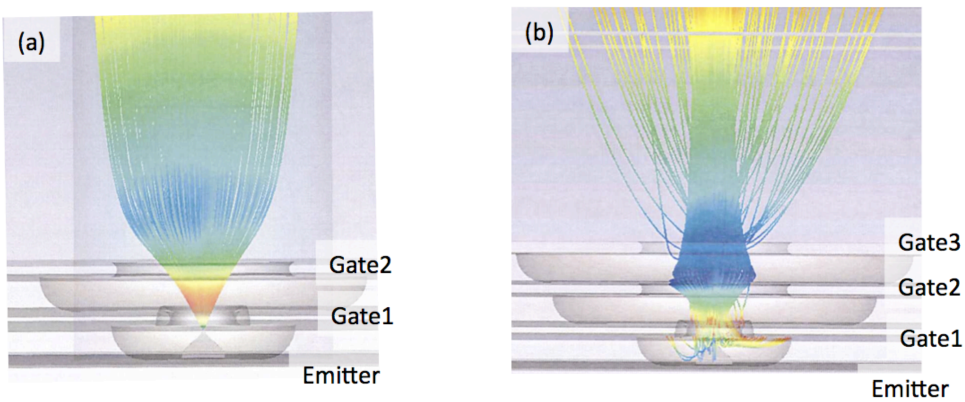


Fig. 8 Preliminary CST simulation of field emission beam generated by (a) double-gate, and (b) triple-gate devices under ~2 MV/m acceleration field.

We investigate these problems in combination numerical simulation, which turned out to be non-trivial because of the large length scale variation, from sub-nanometer scale at the tip, micrometer-scale of the gate structures, and millimeter scale of the external acceleration. Within the present FoKo PhD project, we found that simulation by CST Particle Studio (with the FEA model constructed by us) can approximately reproduce the experiments obtained so far.[29] Preliminary comparison of double-gate and triple-gate devices with PSI FEA structure, the stacked gate structure with planar G2 or G3, indicates that further performance improvement is possible.

### 1.3.6 Synchronization and other issues to be solved

*Synchronization* The requirement for the synchronization of the FEA beam pulse with the FEL bunch is not strict. Since un-deflected FEA beam electrons hit only near the origin on the screen, the principle works even for CW beam, as long as the beam emittance of the probe FEA beam is low. When the FEA beam pulse duration is tens of ps, as assumed in the simulations in Figs. 1-3, the "noise" by the un-deflected electrons is minimized. Synchronization with the jitter in the order of 10 ps is feasible for electrical triggering of FEAs according to the experimental result of the FEA acceleration by the combined diode-RF cavity accelerator.[14] Shorter FEA pulse generation with the improved synchronization is feasible by generating the FEA beam by near infrared laser-induced field emission,[10,16] although experiment with double-gate FEAs is not yet demonstrated.

*Toward quantitative reconstruction of FEL bunch profile* The above simulations show that proposed method is sensitive to detect the asymmetry and rotation of FEL bunches. To reconstruct the actual FEL bunch profile from such deflection orbit of probe beams, analytical procedure seems difficult to establish at this point. However, since the deflection orbits exhibit characteristic variation associated to the transverse shift, asymmetry, and rotation, it is likely that we can solve this non-linear mapping problem by constructing a numerical database for typical bunch profiles in advance as a reference. There is no report of such method in literature. Hence, further research is required to clarify what it takes to make "one"-to-one reconstruction of the FEL bunch profile. However, it seems likely that the resolution of the method can be further improved e.g. by adding one or more probe beams with different incident direction.

### 1.3.7 Plan of research

We therefore propose, I. Systematic investigation of the performance of the double-gate and the triple-gate field emission array cathode, II. Design the electron gun and the beam optics in order to detect the transverse beam size of the FEL bunches and the Injector bunches, and III. Construct a teststand for the transverse beam diagnostics with the field emission deflection sensor.

Part I. We fabricate several single-tip devices and characterize the beam collimation characteristics together with the current-voltage (I-V) characteristics, as well as the electron microscopic characterization of the nanometer-scale tip shape before and after the experiment. The imaging and the I-V will be done in a UHV field emitter test stand at LMN equipped with a faraday cup, a phosphor screen, and a gas leak valve. The gas leak valve will be used to make the gas conditioning (H2, CH4, Ar, Ne etc.) to decrease the work function or blunt the tip apex. The field emitter array device fabrication (the mold wafer fabrication, metallization, demolding, dicing, insulator and gate metal deposition and patterning, electron beam and optical lithography) at LMN clean room is not a trivial task. This will be done as a team using the existing technology and know-hows of the Field-emitter group in LMN as well as the technical help from LMN. The experiment will be compared with a simulation, which will be done by using the CST Particle Studio, by extending the device model developed by the Field emitter group.

Part II. The gun design, in particular, the electro static lens design, will be conducted using COMSOL (elector-static calculation) and SIMION (available in the group), and Particle Studio at the end. Basic design will be done by extending an existing field emission array emission model of the group.

Part III. The actual design will be discussed with SwissFEL and GFA team. For the two dimensional sensitive electron detector, a collaboration via SwissFEL Sigtuna (Swiss-Sweden collaboration), in particular, MediPix collaboration via Mittuniversitet Sundsvall (Christer Fröjdh) and Stockholm Universitet (Fredrik Hellberg, Ansgar Simonsson, Anders Källberg) is planned.

### 1.3.8 Relation of the present research proposal with the currently research in the SwissFEL field-emitter group, LMN

The here proposed research will be conducted in the SwissFEL field-emitter group, LMN,

- S. Tsujino (group leader),
- P. Helfenstein (PhD student, until Oct. 2012),
- Mustonen (SNSF PhD student, until Nov. 2012 (without formal extension)),
- C. Spreu (technician/engineer, 30%).

in collaboration with GFA (Masamitsu Aiba) and SwissFEL (Hans Braun).

The here proposed research, especially the part 1) is closely related the currently running FoKo funded PhD project [19] on the development of the high beam brightness double-gate field emission cathode which ends Oct. 2012.

The here proposed research is also related to the SNSF project (proposal) submitted on April 2012, which is a follow up of the currently running SNSF PhD project (formal ending Nov. 2012), focusing on the physics and the application of ultrafast near infrared laser-induced field emission using PSI FEAs. Therefore, the exact scope of the here proposed research is different from the SNSF project.

## 1.4 Time Frame

| Start date | Activity | Milestones | End date |
|---|---|---|---|
| 7.2012 | Solicitation/ evaluation of a candidate | Employment of a Post Doc | 12.2012 |

**PD-WP1: Single-tip multi-gate field emitters (LMN)**

| Start date | Activity | Milestones | End date |
|---|---|---|---|
| 1.2013 | Design and construction of field emission test chamber w/Faraday cup, beam imager, and optical access from oblique and perpendicular angles<br><br>Design and fabrication of multiple single-tip devices with single- and double-gate electrodes<br><br>PIC simulation of multiple-gate field emitter array beam characteristics and semi-analytic analysis of beam aberration and distortion | Correlation of the field emission characteristics (I-V and collimation properties) and emitter tip shape<br><br>Impact of the noble gas processing on the field emission | 7.2013<br><br>7.2013 |
| | | Correlation between the transverse beam spread and the gate electrode structure | 1.2014 |
| | | Comprehensive analysis of the aberration and distortion of multiple-gate field emitter electron source | 5.2014 |
| | | Optimization of field emission beam brightness in terms of the device and gun structures | 10. 2014 |

**PD-WP2: Electron fork (PSI[SYN-SwissFEL]-Sundsvall/Stockholm)**

| | | | |
|---|---|---|---|
| 3.2013 | Evaluation of field emission beam resolution Prototyping of the deflection sensor mockup<br><br>Concept and design of electron gun optics | Optimization of collimation characteristics of double-gate field emitters<br><br>Quantitative assessment of deflection sensitivity | 11.2013 |
| 12.2013 | Construction of test stand for transverse beam diagnostics with the field emission deflection sensor | Experimental evaluation of the deflection sensor performance at the SwissFEL Injector test facility | 6.2014 |

# 2. Funds, Partners

## 2.1 Equipment Needed

FEA characterization of part 1) will be conducted in the field-emission lab (ODRA) of the SwissFEL field emitter group, LMN using a UHV field emission characterization chamber equipped with a phosphor screen (incl. MCP) and a Faraday cup. Necessarily instruments (high voltages sources, high-voltage pulsers, oscilloscopes, camera and basic PC control hardwares and softwares, etc.) are available.

Fabrication of FEAs requires extensive clean room work using photolithography, wet and dry etching and patterning, oxidation, metal and insulator deposition, and electron-beam lithography. The clean room facility of LMN is equipped with the necessarily tools.

The actual fabrication will be conducted by the proposed post-doc with the technical support of a technician partly associated with the field emitter group with the aid of LMN-clean room technical staffs.

Basic design of the electron optics (field emission gun and the configuration of the geometry) will be conducted using several available softwares, COMSOL for electro-statics, SIMION for electro-statics and simple particle tracking with approximate space-charge effect of the beam, and CST Particle Studio (PSI license).

The analysis of the collimation performance of double-gate FEAs turned out to be a non-trivial problem that have been reported in the past by several authors without detailed comparison with experiments. Within the current FoKo PhD project, we are constructing a FEA model using Particle Studio that can give simulation results similar to experiments. We continue to refine the FEA model of the Particle Studio with the optimization of the double-gate and triple-gate FEAs.

## 2.2 Project-specific Personnel Planning of the Research Lab

| **Staff requirement:** | during project duration (PJ/J) (incl. present proposal) | | after project termination (PJ/J) | |
|---|---|---|---|---|
| Financing: | PSI | Partner | PSI | Partner |
| Soichiro Tsujino (LMN-SYN)<br>Hans-Heinrich Braun (SwissFEL) | 0.5<br>0.1 | | | |
| Post Doc N.N, | 1.0 | | | |
| Technician<br>Christian Spreu (LMN-SYN)<br>LMN-technical staffs | <br>0.3<br>0.3 | | | |
| Others (e.g.. GFA, LOG & construction) | | | | |

are follow-up projects already planned? ☐ yes ☒ no

### 2.3 External Partners

**MediPix via SwissFEL-Sigtuna collaboration**

Christer Fröjdh, Dr. (Mittuniversitet Sundsvall)

Frederik Hellberg, Dr. (Stockholm Universitet)

## 3. Technology Transfer

### 3.2 Own Patents

- S. Tsujino, M. Paraliev, C. Gough, E. Kirk and P. Helfenstein, *Field emission cathode structure and driving method thereof,* Preliminary European Patent filing (July, 2011).

- E. Kirk and S. Tsujino, *Method to produce field-emitter arrays with controlled apex sharpness,* International Patent application (WO/2009/156242).

**References**


1. P. Tehenbaum and T. Shintake, Measurement of small electron-beam spots, Ann. Rev. Nucl. Part. Sci. Vol. 49, pp.125-62 (1999).
2. Å. Andersson, M. Böge, A. Lüdeke, V. Schlott, and A. Streun, *Determination of a small vertical electron beam profile and emittance at the Swiss Light Source*, Nuc. Instrum. Method. **A591**, pp. 437-446 (2008).
3. M. Dehler, A. E. Candel, and E. Gjonaj, Full-scale simulation of a field-emitter arrays based electron source for free electron lasers, J. Vac. Sci. Technol. B **24** (2), pp. 892-897 (2006).
4. A. E. Candel, Simulation of Electron Source for Next - Generation X-Ray Free Electron Laser, Thesis (ETH Zurich Nr. 16181, 2005).
5. M. Dehler, Design and modeling of field emitter arrays for a high brilliance electron source, in Proc. 9$^{th}$ ICAP, Chamonix, France, Oct. 2–6, 2006, pp. 114–117.
6. C. Leemann, A. Streun, A. Wrulich, *Beam characterization for the field-emitter-array cathode-based low-emittance gun*, Phys. Rev. ST Accel. Beams **10**, 071302 (2007).
7. S. C. Leemann, Characterization of electron bunches from field emitter array cathodes for use in next generation X-Ray free electron lasers, Thesis (EPFLausanne, no 3724, 2007).
8. E. Kirk and S. Tsujino, *Method to produce field-emitter arrays with controlled apex sharpness*, International Patent application (WO/2009/156242).
9. E. Kirk, S. Tsujino, T. Vogel, K. Jefimovs, J. Gobrecht, A. Wrulich, *Fabrication of all-metal field emitter arrays with controlled apex sizes by molding*, J. Vac. Sci. Technol. B **27**, 1813 (2009).
10. S. Tsujino, P. Beaud, E. Kirk, T. Vogel, H. Sehr, J. Gobrecht, and A. Wrulich, *Ultrafast electron emission from metallic nanotip arrays induced by near infrared femtosecond laser pulses*, Appl. Phys. Lett. **92**, 193501 (2008).
11. S. Tsujino, F. le Pimpec, J. Raabe, M. Buess, M. Dehler, E. Kirk, J. Gobrecht, and A. Wrulich, Static and optical field enhancement in metallic nanotips studied by two-photon photoemission

microscopy and spectroscopy excited by picosecond laser pulses, Appl. Phys. Lett. **94**, 093508 (2009).

12. S. Tsujino, P. Helfenstein, E. Kirk, T. Vogel, C. Escher, and H.-W. Fink, *Field-emission characteristics of molded molybdenum nanotip arrays with stacked collimation gate electrodes*, IEEE Electron Device Letters, vol. 31, No. 9, September 2010, pp.1059-1061.
13. S. Tsujino, M. Paraliev, E. Kirk, T. Vogel, F. Le Pimpec, C. Gough, S. Ivkovic, and H.-H. Braun, *Nanosecond pulsed field emission from single-gate metallic field emitter arrays fabricated by molding*, J. Vac. Sci. Technol. **29**, 02B117 (2011).
14. S. Tsujino, M. Paraliev, E. Kirk, C. Gough, S. Ivkovic, and H.-H. Braun, *Sub-nanosecond switching and acceleration to relativistic energies of field emission electron bunches from metallic nano-tips*, Phys. Plasmas **18**, 064502 (2011); Selected for June 27, 2011 issue (Volume 23, Issue 25) of Virtual Journal of Nanoscale Science & Technology.
15. P. Helfenstein, E. Kirk, K. Jefimovs, T. Vogel, C. Escher, H.-W. Fink, and S. Tsujino, *Highly collimated electron beams from double-gate field emitter arrays with large collimation gate apertures*, Appl. Phys. Lett. **98**, 061502 (2011).
16. A. Mustonen, P. Beaud, E. Kirk, T. Feurer, and S. Tsujino, Five picocoulomb electron bunch generation by ultrafast laser-induced field emission from metallic nano-tip arrays, Appl. Phys. Lett. **99**, 103504 (2011).
17. S. Tsujino, M. Paraliev, E. Kirk, and H.-H. Braun, Homogeneity improvement of field emission beam from metallic nano-tip arrays by noble-gas conditioning, Applied Physis Letters **99**, 073101 (2011).
18. S. Tsujino, T. Feuer, P. Beaud, B. Oswald, Femtosecond electron dynamics and nano-optic enhancement of laser-assisted field-emission from metallic nano-tip arrays with controlled apex-sizes, (SNSF project, one PhD student, no. 200021_125084, Dec. 2009-).
19. S. Tsujino, H.-W. Fink, *Development of high-brightness field emission cathode*, PSI internal project (one PhD student) funded via FoKo proposal (May 2009-).
20. B. D. Patterson, R. Abela, H.-H. Braun, U. Flechsig, R. Ganter, Y. Kim, E. Kirk, A. Oppelt, M. Pedrozzi, S. Reiche, L. Rivkin, T. Schmidt, B. Schmitt, V. N. Strocov, S. Tsujino, and A. F. Wrulich, *Coherent science at the SwissFEL X-ray laser, New J. Phys.* **12**, 035012 (2010).
21. C.-M. Tang, A. C. Ting and T. Swyden, *Field-emission arrays – a potentially bright source*, Nuclear Inst. Meth. A **318**, 353 (1992).
22. J. C. H. Spence, *Experimental high-resolution electron microscopy* (Clarendon Press, Oxford, 1981).
23. A. Crewe, *Scanning Electron Microscope: is High Resolution Possible?*, SCIENCE **154**, 729 (1966).
24. C. A. Spindt*, A thin-film field-emission cathode*, J. Appl. Phys. **39**, 3504 (1968).
25. P. R. Schwoebel, C. A. Spindt, and C. E. Holland, *High current, high current density field emitter array cathodes*, J. Vac. Sci. Technol. B **23**, 691 (2005).
26. M. Nakamoto, T. Hasegawa, T. Ono, T. Sakai, and N. Sakuma, *Low operation voltage field emitter arrays using low work function materials fabricated by transfer mold technique*, Tech. Dig. - Int. Electron Devices Meet. **1996**, 297.
27. T. Soda, M. Nagao, C. Yasumuro, S. Kanemaru, T. Sakai, N. Saito, Y. Neo, T. Aoki, and H. Mimura, *Fabrication of Volcano-Structured Double-Gate Field Emitter Array by Etch-Back Technique*, Jpn. J. Appl. Phys. 47, 5252 (2008).
28. A. Koike, T. Fujino, Y. Neo, H. Mimura, T. Yoshida, T. Nishi, M. Nagao, H. Murata , *A functional tiny electron gun for a true microcolumn*, Technical digest, 24$^{th}$ International Vacuum nanoelectronics Conference, p. 107 (2011).
29. P. Helfenstein, and S. Tsujino, *Field emission beam collimation characteristics of stacked-double-gate field emitter array cathodes* (in preparation, 2012).