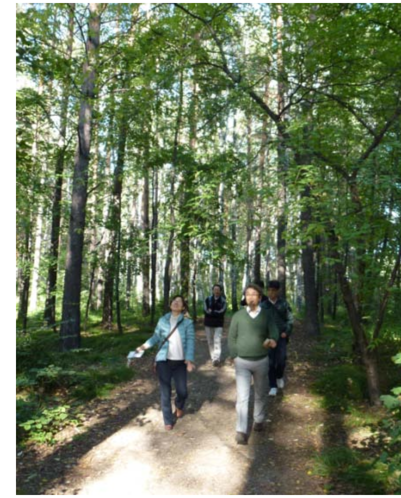
第77回ERL検討会

ERL2013 WG1(電子銃＆入射器関係) 報告

2013年10月24日(木)　14：00～

報告：山本将博



ERL2013の口頭発表スライドは下記のリンクよりほぼ全てが参照できます。
http://ssrc.inp.nsk.su/Conf/ERL2013/Presentations/

報告の概要

- ERL2013 WG1での報告（口頭9件、ポスター4件）
  Cornell大、BNL、HZB、HZDR、BINP、IHEP(poster)、Peking(poster)
  JAEA（西森）、KEK（坂中,本田,山本）
  J-Lab, DaresburyからWG1での報告は今回は無かった。

- 電子銃開発
  DC-gun: JAEA, KEK, IHEP
  SRF-gun: HZDR, HZB, BNL, Peking(DC-SRF Gun)

- 入射器調整、ビーム診断
  Cornell, HZDR, HZB, KEK

- フォトカソード開発、評価
  Cornell (Na_2KSb), BINP (GaAs), HZB&BNL (CsK_2Sb)

- Laser開発
  HZB、HZDR (MBI&DESY)

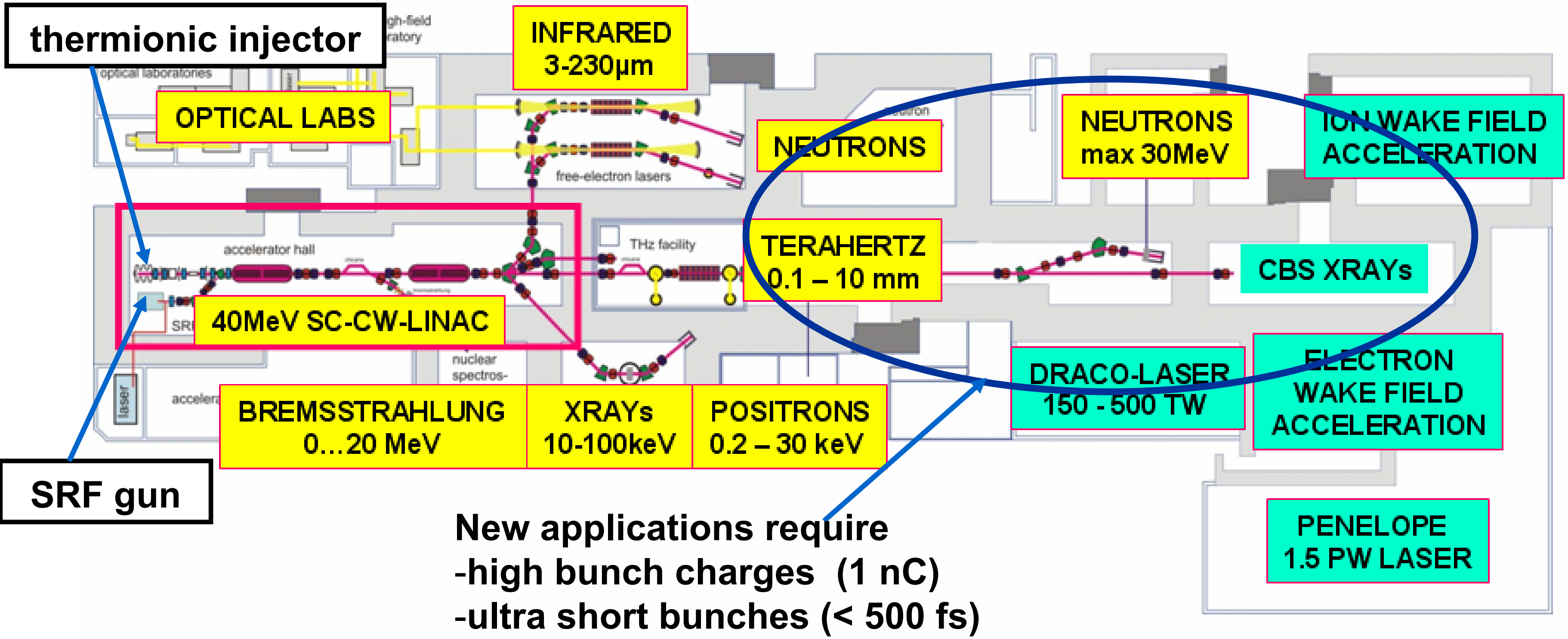
SRF-Gun

設計値

- HZDR – 3.5 cell, 9 MeV, < 2 mA
- BNL – 1.5 cell, 2 MeV, 500 mA
- HZB – 1.4 cell, 2 MeV, 100 mA

ELBE User Facility

J. Teichert氏スライドより



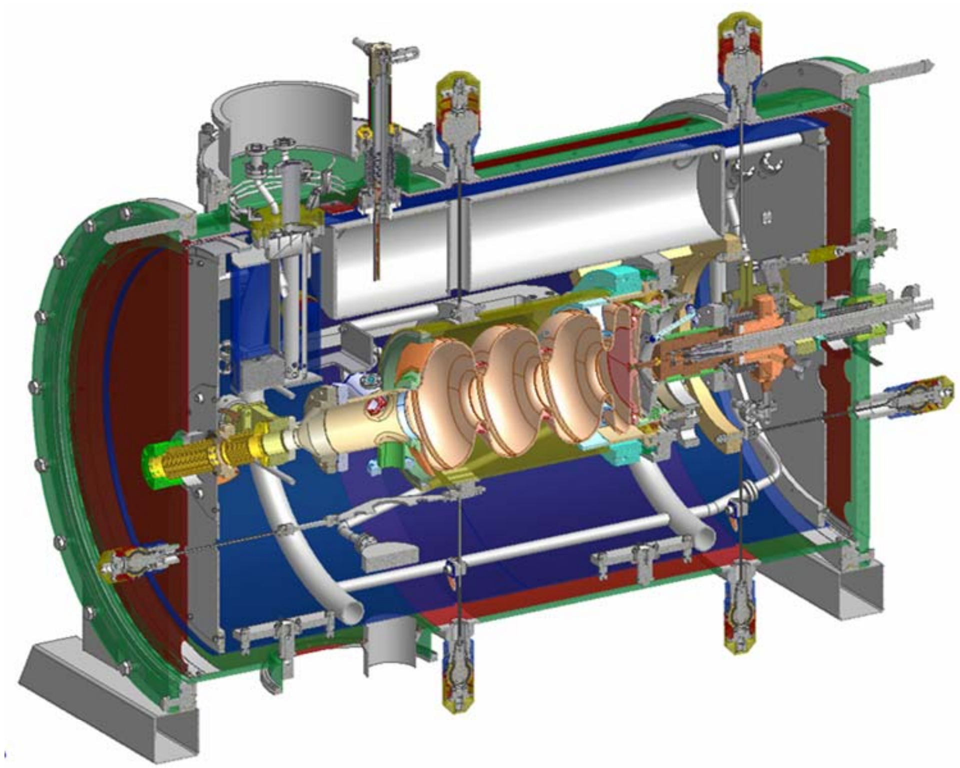
New applications require
-high bunch charges (1 nC)
-ultra short bunches (< 500 fs)
-low transverse emittance (1 mm mrad)

Accelerator Research an Development at ELBE:

Superconducting RF Photoelectron Injector

Application

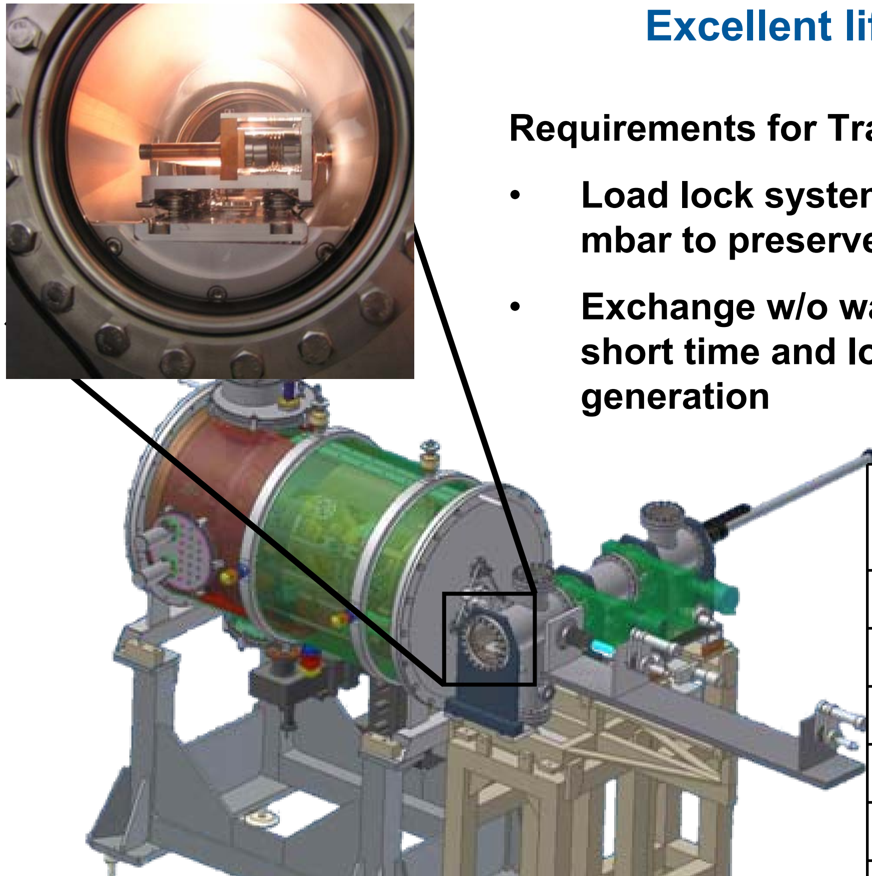
•high peak current operation for CW-IR-FELs with 13 MHz, 80 pC
•high bunch charge (1 nC), low rep-rate (<1 MHz) for pulsed neutron and positron beam production (ToF experiments)
•low emittance, medium charge (100 pC) with short pulses for THz-radiation and x-rays by inverse Compton backscattering



Design

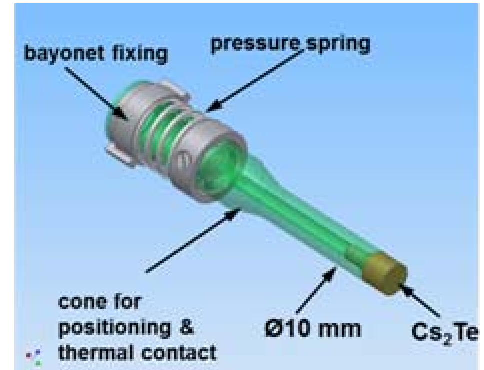
medium average current:
1 - 2 mA (< 10 mA)
high rep-rate:
500 kHz, 13 MHz and higher
low and high bunch charge:
80 pC - 1 nC
low transverse emittance:
1 - 3 mm mrad
high energy:
≤ 9 MeV, 3½ cells (stand alone)
highly compatible with ELBE cryomodule (LLRF, high power RF, RF couplers, etc.)
LN2-cooled, exchangeable high-QE photo cathode

Excellent lifetime of Cs2Te PC in SRF gun



Requirements for Transfer:

- **Load lock system with < 10^{-9} mbar to preserve QE ≥ 1 %**
- **Exchange w/o warm-up & in short time and low particle generation**



Cathode	Operation days	Extracted charge	Q.E. in gun
#090508Mo	30	< 1 C	0.05%
#070708Mo	60	< 1 C	0.1%
#310309Mo	109	< 1 C	1.1%
#040809Mo	182	< 1 C	0.6%
#230709Mo	56	< 1 C	0.03%
#250310Mo	427	35 C	1.0%
#090611Mo	65	< 1 C	1.2%
#300311Mo	76	2 C	1.0 %
#170412Mo	From 12.05.2012	265 C	~ 0.6 %

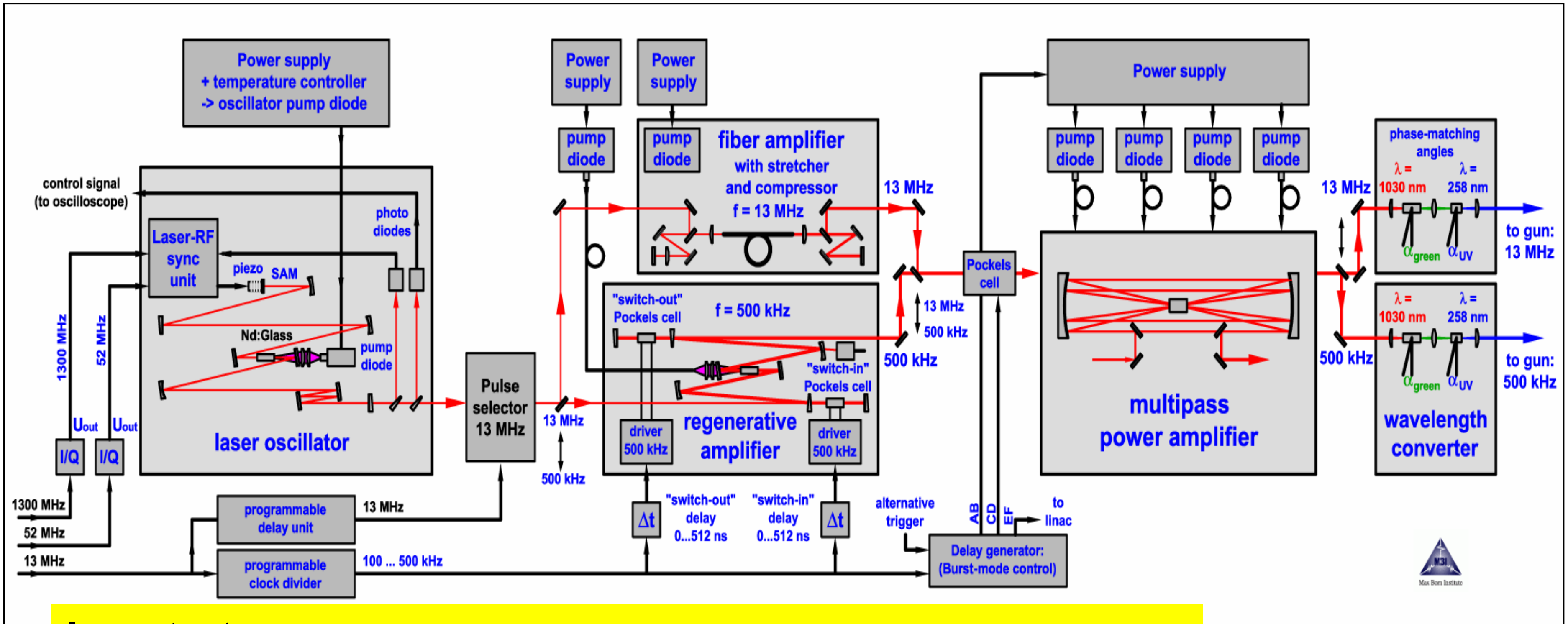
- **fresh QE 8.5%, in gun 0.6%**
- **total beam time 600 h**
- **extracted charge 265 C**

01.08.2013

problems: multipacting, QE drop-down during storage

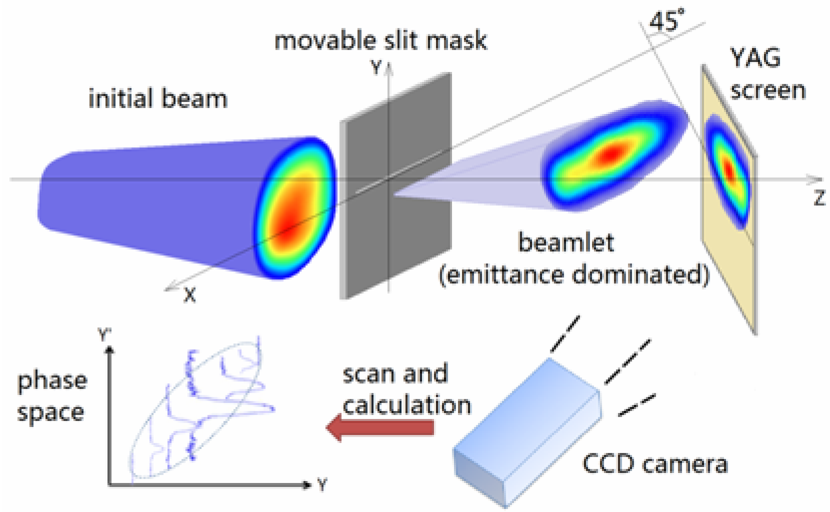
UV Laser system developed by MBI:

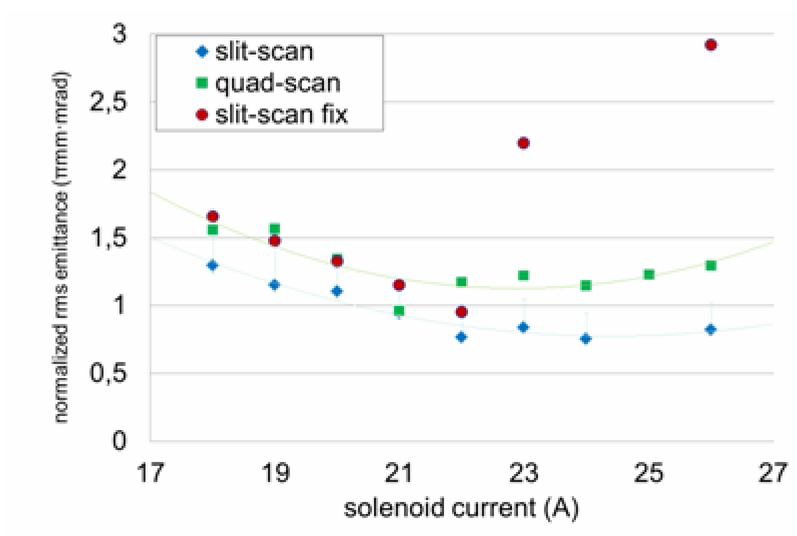
- Large flexibility in repetition rate and time structure (burst)
- Conversion to the UV (λ ~ 260 nm) at ~ 1 W power
- Synchronisation with RF of the linac + full remote control of the laser
- Different repetition rates + different pulse durations:
  a) 13 MHz: 3 ps FWHM Gaussian   b) 100/250/500 kHz: 12 ... 15 ps FWHM Gaussian

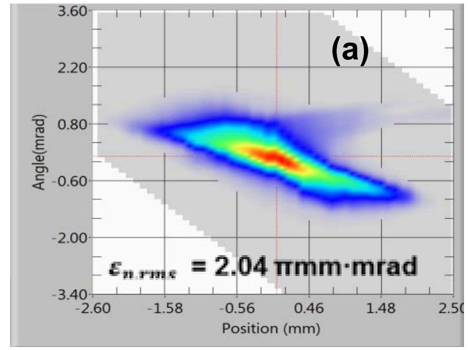


Important
- **13 MHz allow to demonstrate high-current operation of the gun**
- **Parameters fullfil the requirements for user operation at ELBE**

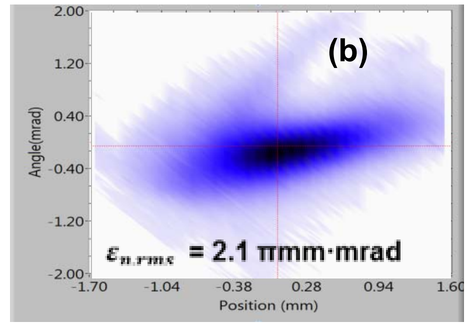
NEW: Emittance Measurements with Single Slit Scan







Beam



Dark current

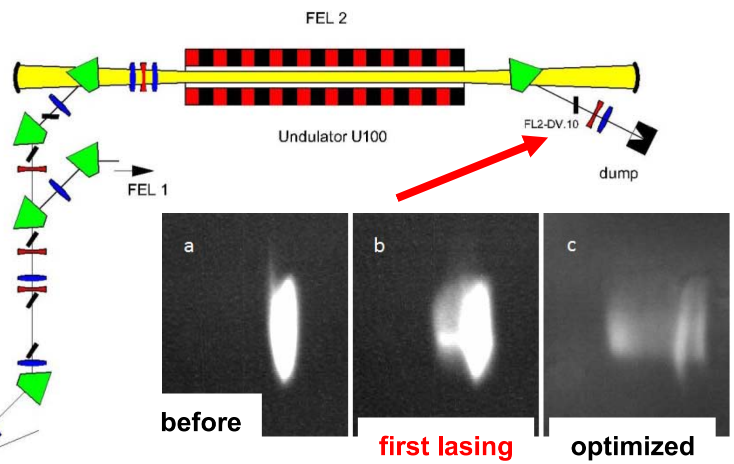
SRF-Gunで発生した暗電流がそのまま主加速器へ運ばれないように途中でkickする装置をdogleg前に入れている。

Pengnan Lu

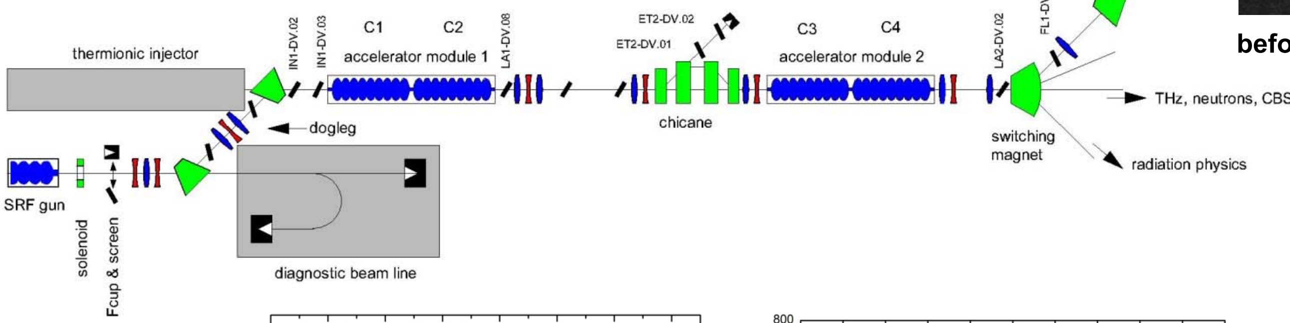
First FEL Operation with SRF Photo Gun at ELBE

E_{kin} at gun exit	3.3 MeV
Micro pulse repetition rate	13 MHz
Macro pulse repetition rate / length	1.25 Hz / 2 ms
Beam energy at FEL	27.9 MeV
Bunch charge / beam current	20 pC / 260 μA
Photo cathode	Cs_2Te
RMS bunch length	1.6 ps
Normal. RMS emittance	1 mm mrad

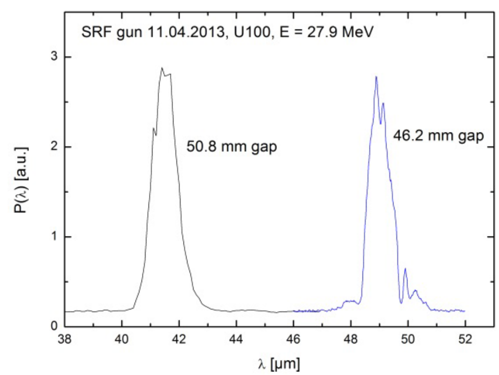
ELBE infrared FEL (20 – 250 μm)



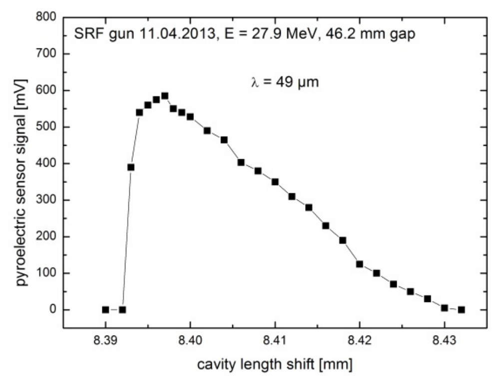
April 11, 2013



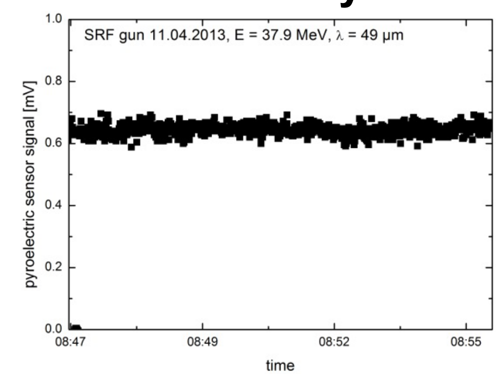
stabilty



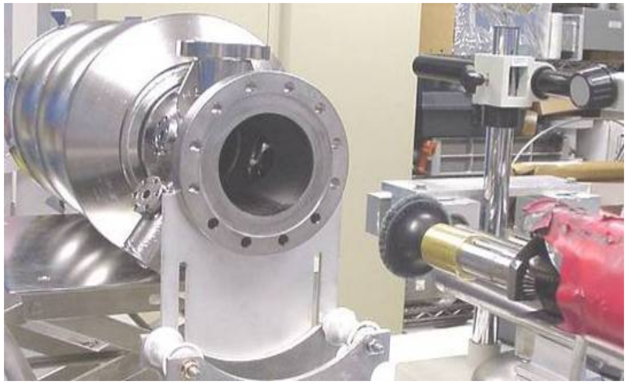
FEL spectra

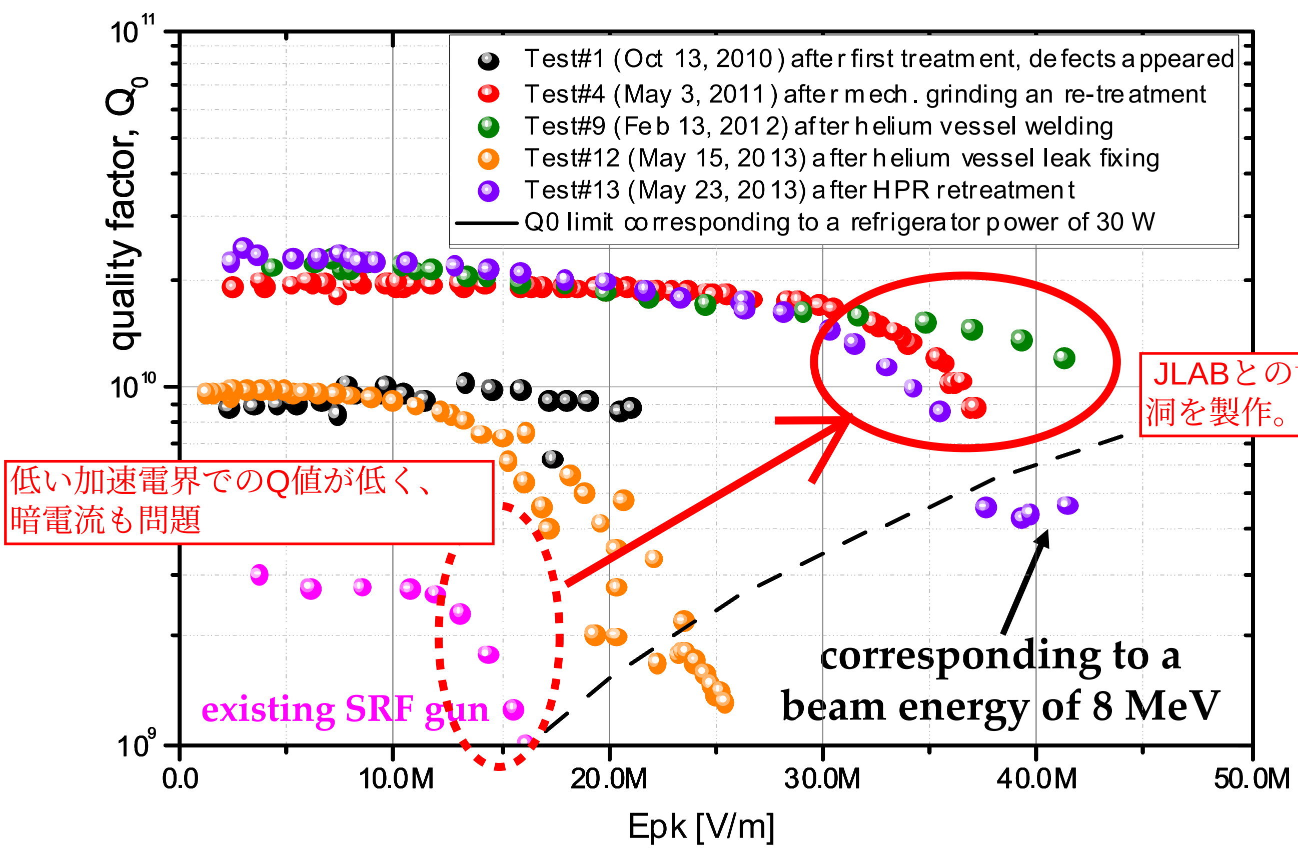


FEL detuning curve



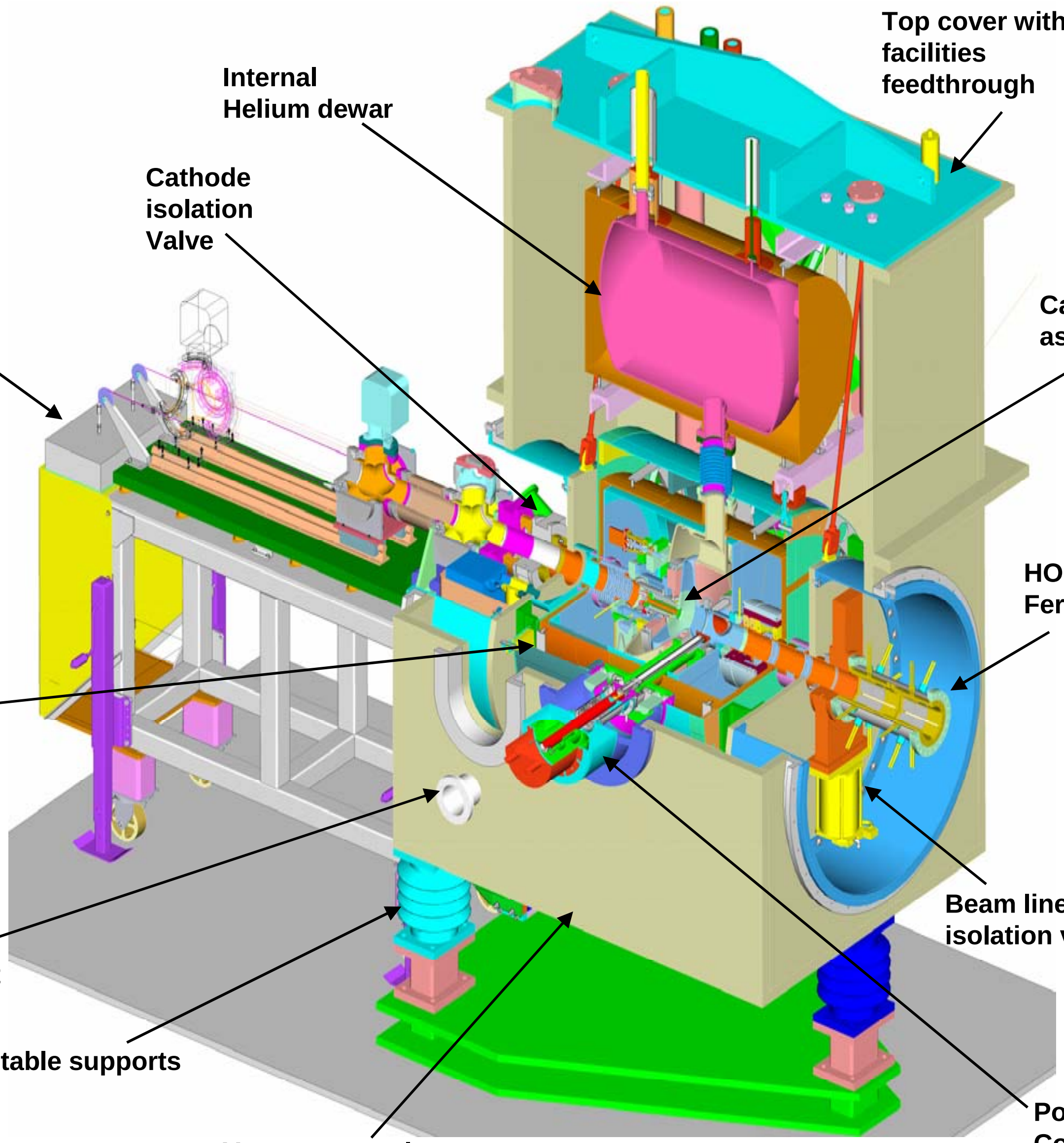
NEW SRF GUN WITH HIGH ACCELERATION GRADIENT





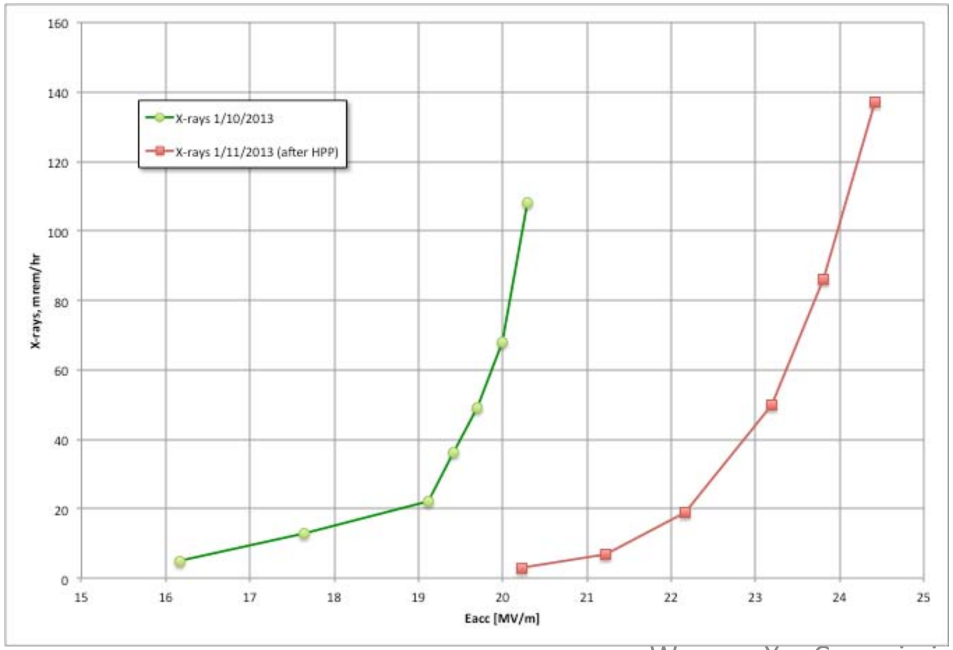
704 MHz SRF gun

BNL: Wencan Xu氏スライドより



- The 703.75 MHz ½ - cell SRF gun has two Fundamental input Power Couplers (FPCs) allowing to deliver 1 MW of RF power to a 0.5 A electron beam at energy gain of 2 MeV.
- The cavity active length is 8.5 cm, tuning range is 1.2 MHz (1 mm of cavity deformation).
- HOM damping is provided by an external beamline ferrite load with a ceramic break.

Commissioning of SRF gun w/o a cathode insert

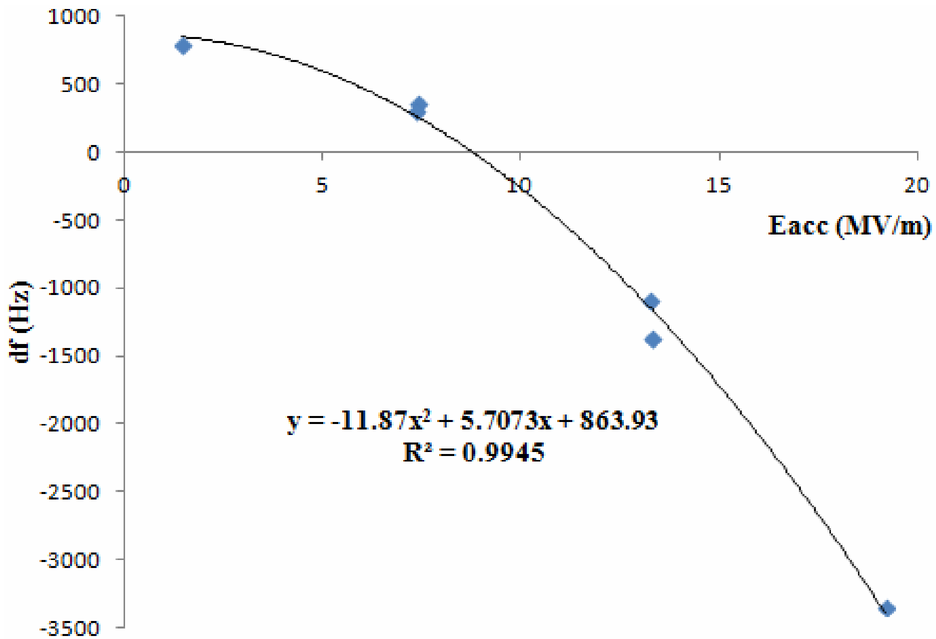


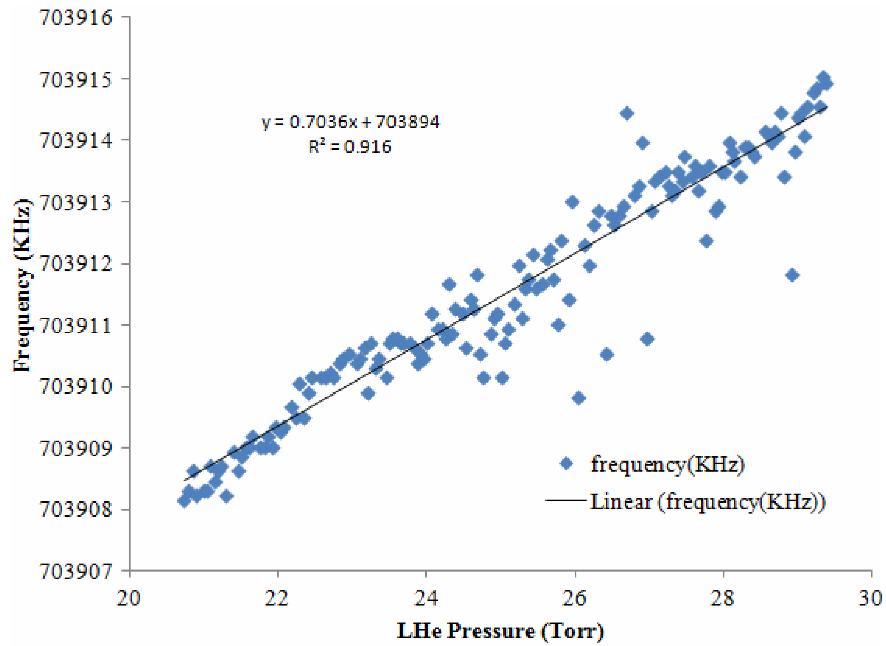
- Prior to assembly into the gun cryomodule, its two FPCs were conditioned off-line in standing wave mode with full reflection at variable RF phase. Maximum power was 250 kW in pulse mode (limited by klystron collector) and 125 kW in CW (administrative limit).
- The gun cryomodule was assembled last year and is installed in the ERL block house. Its 1 MW CW klystron, cryogenic system and other ancillary systems are fully operational.

The initial commissioning of the gun without a cathode is complete (Nov. 2012 to Mar. 2013) with the gun cavity achieving 2 MV (the original design voltage) and 220 kW of RF power in CW mode.

In pulsed mode, with a 0.7 ms pulse duration and 1 Hz repetition rate, the RF power was up to 400 kW. This allowed to do high-power RF processing of field emission in the cavity.

LFD & sensitivity to He pressure





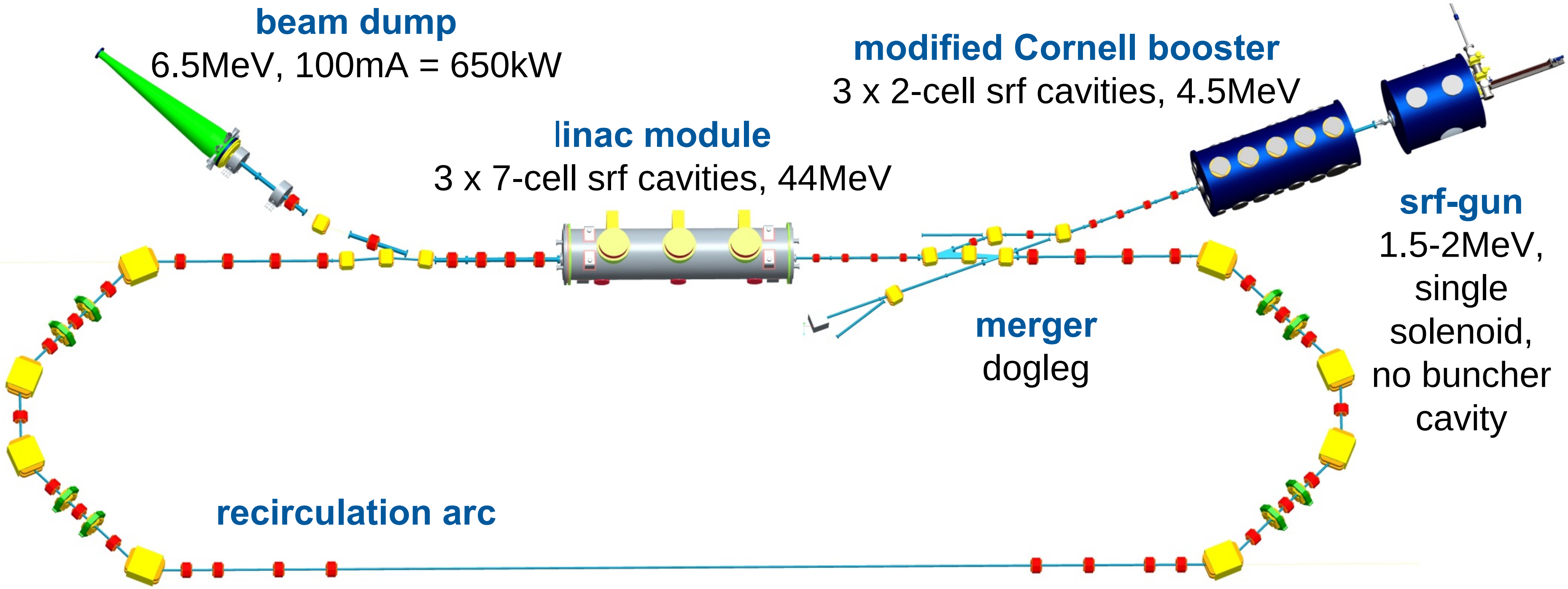
- The Lorentz force detuning coefficient is -11.9 Hz/(MV/m)^2.
- The cavity frequency is very sensitive to He bath pressure fluctuations: 704 Hz/Torr.

B*ERL*inPro @ Helmholtz-Zentrum Berlin

B*ERL*inPro = Berlin Energy Recovery Linac Project

HZB: Roman Barday氏スライドより

100mA / low emittance technology demonstrator (covering key aspects of large scale ERL)

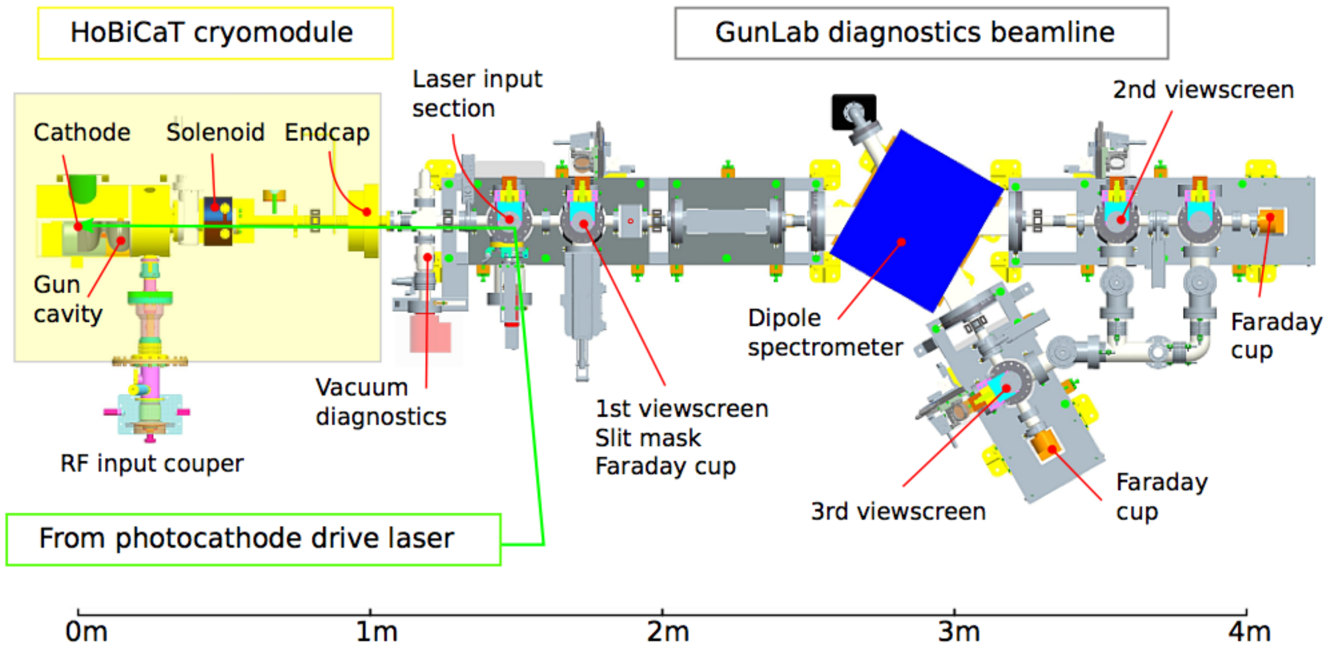


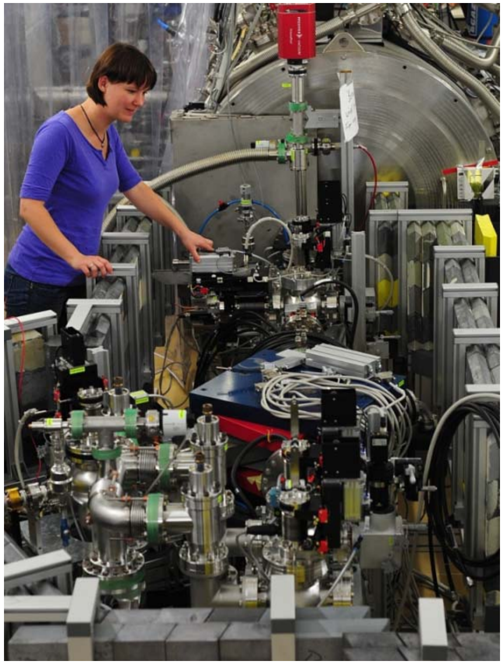
Project start 2011,
fully funded (36.5 Mio€)

already 11,8 Mio€ spent (power transmitters, srf-gun development)

	Basic Parameter
max. beam energy	**50MeV**
max. current	**100mA (77pC/bunch)**
normalized emittance	**1 π mm mrad**
bunch length (straight)	**2 ps or smaller**
rep. rate	**1.3GHz**
losses	**< 10^{-5}**

Gun0: Install SRF gun cavity in HoBiCaT cryomodule, add drive laser and electron beam diagnostics





Study RF properties → Q_o vs E_{acc}, LLRF microphonics, operation with TTF-III coupler, interaction with SC solenoid, steering magnet

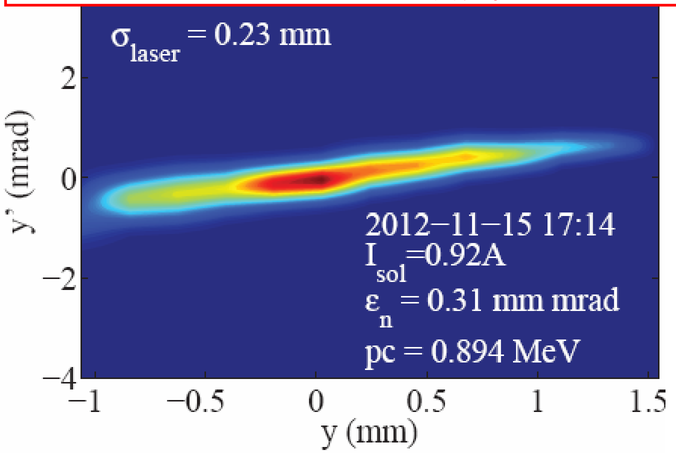
Beam dynamics studies → Viewscreens, slit mask, Faraday cups, dipole spectrometer

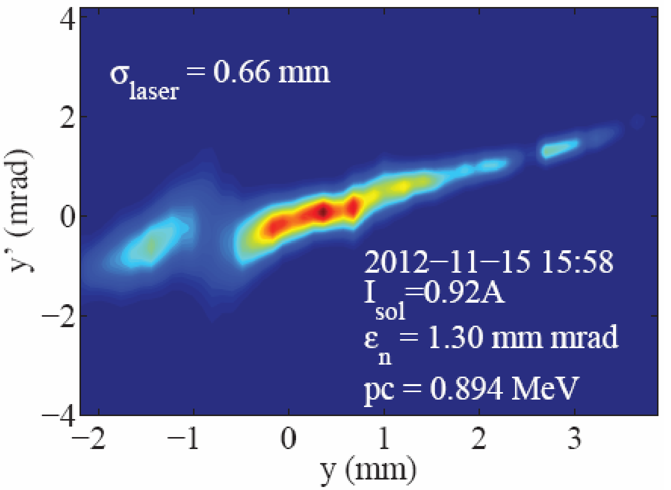
Cathode performance → measure QE maps, thermal emittance and dark currenet, do laser cleaning

→ **Learn for next generation SRF gun**

Gun0 results from emittance and phase space measurements: emittance dominated by rough and structured emission surface

Pbカソードは Cavityに直接蒸着からプラグ方式にすることでエミッタンスは改善。





M. Schmeißer, et al.,
Proc. of IPAC 2013, MOPFI002

Findings with cavity 0.1, Pb film directly on Nb wall:

Measured emittance at low bunch charge with solenoid scan technique

Found strong scaling of emittance with laser spot size.

Largest contributions from solenoid astigmatism and bifurcated emission from cathode.

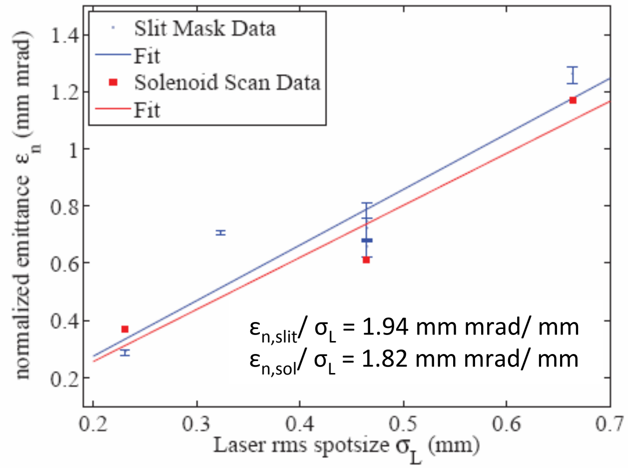
Cathode film covered with protrusions from Pb droplets.

Findings with cavity 0.2, Plug coated with Pb:

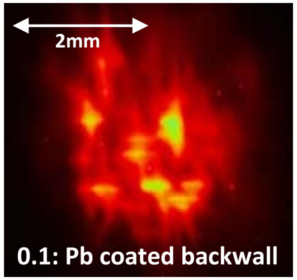
Measured phase space with slit mask.

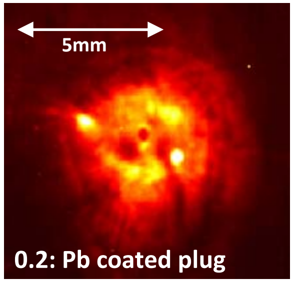
Emittanceof 0.2 three times lower than 0.1, improved cathode surface with less protrusions.

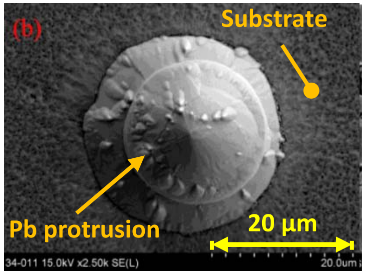
Shorter arc and slit aperture avoid formation and reach of micro-droplets

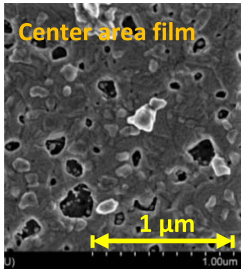


Emission spot imaged with solenoid on first view screen









Beam dynamics driven design of 1.4cell cavity for 2.5 MeV ERL class, average power limited, SRF photoinjector

Beam dynamics requires…

high launch field for low intrinsic emittance, and rapid acceleration to mitigate space charge effects,

radial field in cathode region → initial focusing to minimize emittance growth due to aberrations.

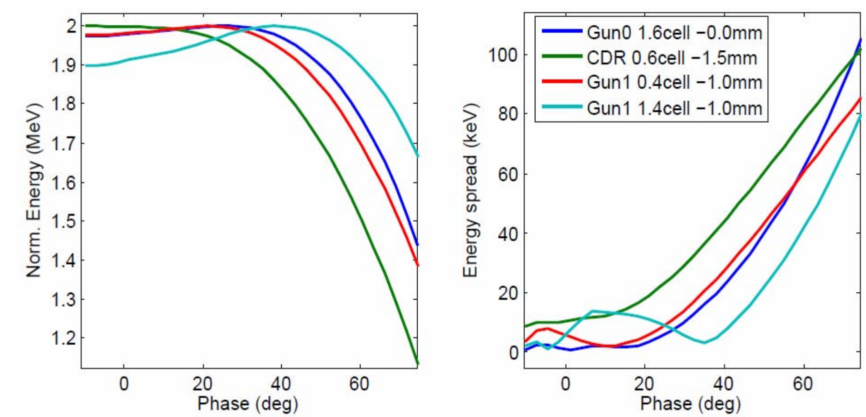
SRF operations wants…

min. ratio E_{pk}/E_{cath} to reduce probability of field emission,

min. H_{pk}/E_{pk} to minimize losses,

max. R/Q for TM_{010} π Mode,

propagation of HOMs out of cavity.



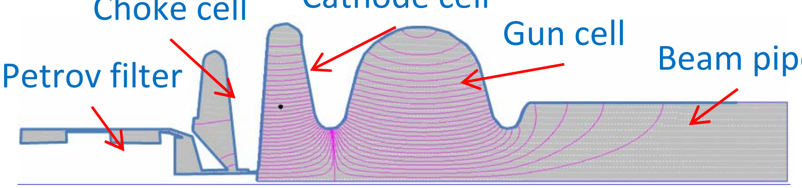
T. Kamps, LINAC 2012

Loop through cavity design and optimize SRF criteria, field flatness, target frequency

Check longitudinal beam dynamics with single particle energy vs. phase scans.

Take settled design to multi particle ASTRA parameter studies

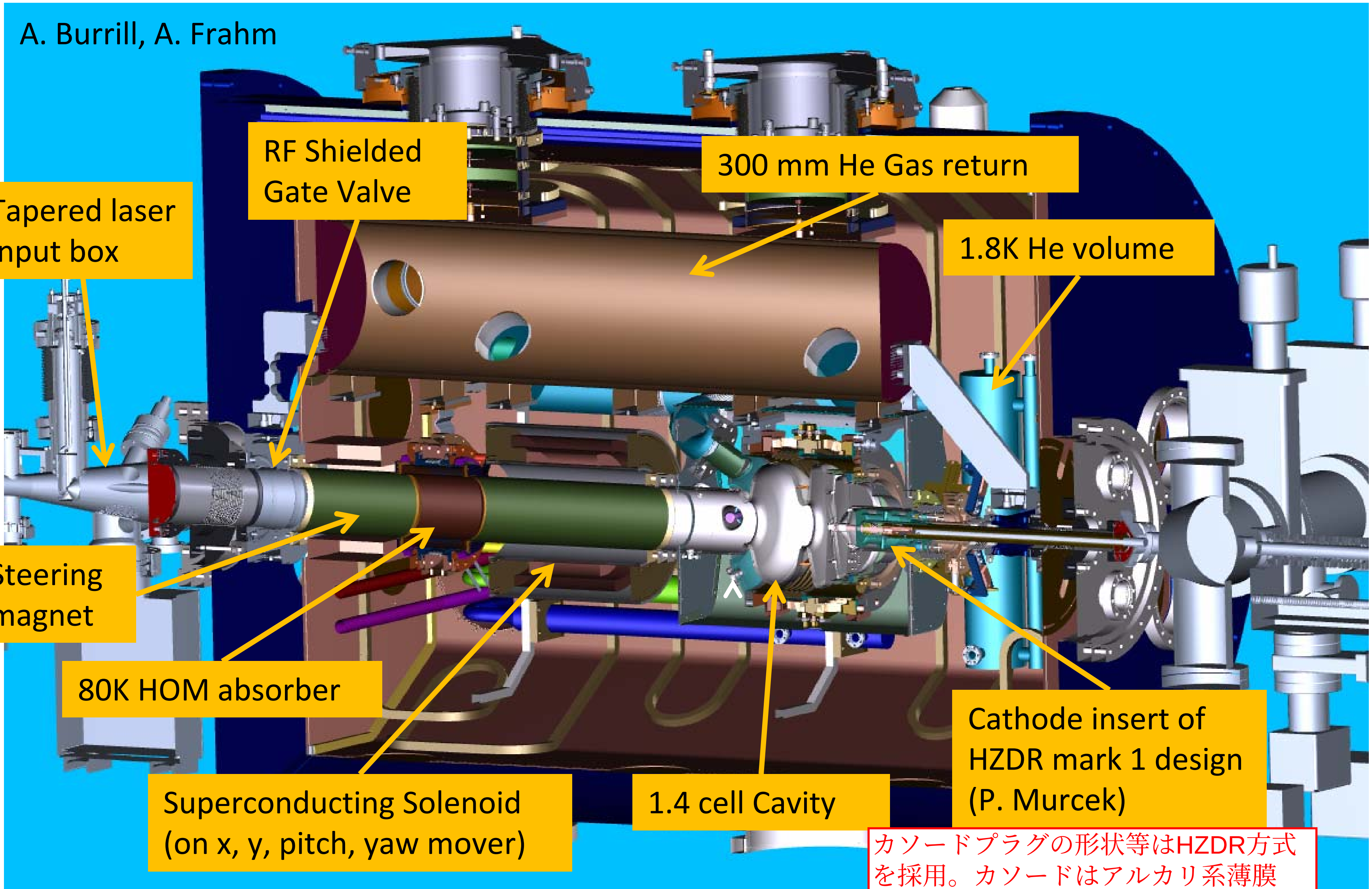
Elliptical 1.4 cell 1.3 GHz with Choke filter



A. Neumann, LINAC 2012

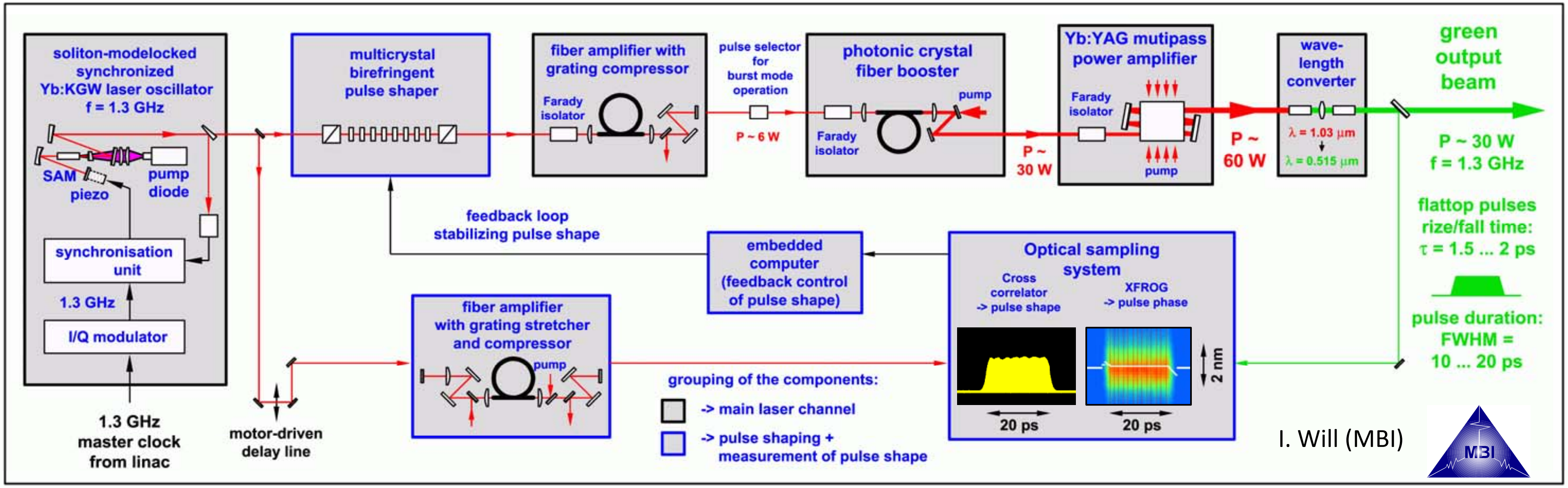
R/Q	= 150 (190) Ω	At E_0	= 30 MV/m
H_{pk}/E_{pk}	= 2.3 (4.4) mT/(MV/m)	E_{pk}	= 45 MV/m
E_{pk}/E_0	= 1.5 (1.86)	E_{kin}	= 2.4 MeV
E_{cath}/E_0	≈ 0.8 (1.0)	Φ_{Emax}	= 50 deg
		E_{cath}	= 24 MV/m
Values for 1.4cell (1.6cell)		E_{launch}	= 18.4 MV/m

The cold mass includes cathode insert shaft, gun cavity, solenoid and steering magnets, HOM absorber and RF/cryo infrastructure



カソードプラグの形状等はHZDR方式を採用。カソードはアルカリ系薄膜（Cs2Te,CsK2Sb等）

2.) High average power 1.3 GHz repetition rate with fiber and Yb:YAG booster amplifier for 60 W at IR serving BERLinPro



(pulse shape + XFROG: measurement at another system at MBI)

Challenges on the path: Development of …

1.3 GHz oscillator with synchronisation ≤ 1ps to external master.

Booster amplifier to bring average power at IR > 60 W → thin-disk geometry.

Diagnostics mode with reduced duty cycle and repetition rate, from 24 W at 1.3 GHz down to 0.2 μW single pulses at 10 Hz (10^8).

Pulse selector and picker with rise/fall time faster than bunch spacing of 770 ps.

Conclusions

Getting a head start with Gun0 proved very valuable → many lessons learnt

- Cavity design and operation.
- Beam diagnostics and phase space characterization.
- Cold mass solenoid.
- Laser beam transport and diagnostics.

Now the focus is on

- Realization of ERL class gun cavity.
- Cathode/ cavity interface.
- Photocathode growth and characterization.
- Field emission studies.
- Improvement of beam diagnostics of GunLab for slice measurements.
- Drive laser upgrade.

Plan to start Gun1 with beam September 2014.

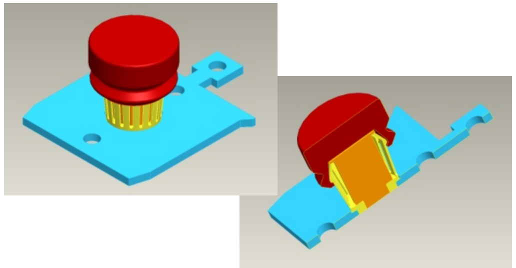
Preparation and analysis system to grow CsK2Sb cathodes and study characteristics before/after use in gun and under gases

Preparation chamber:

Four evaporation sources (two simultaneous), mass spectrometer, two quarz crystal microbalances, photocurrent measurement, and sputter gun for substrate preparation

Manipulator

allows sample heating and cooling, application of bias voltage



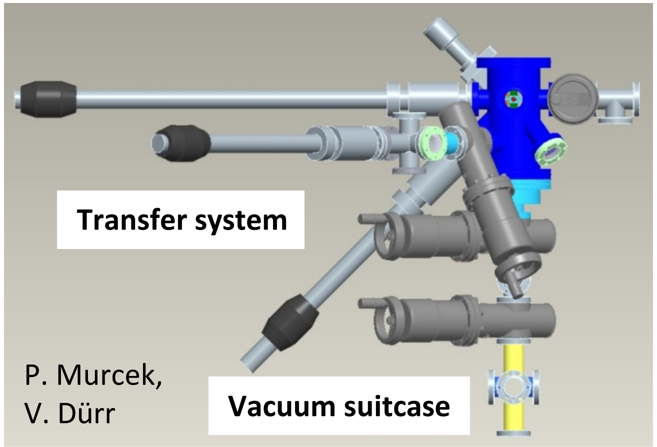
Cathode plug on sample holder

Analysis chamber:

XPS, LEIS, energy analyzer and momentatron for chemical composition, depth profiling, surface composition, deposition rate, spectral response and intrinisc emittance measurement.

Transfer chamber/ suitcase:

under development



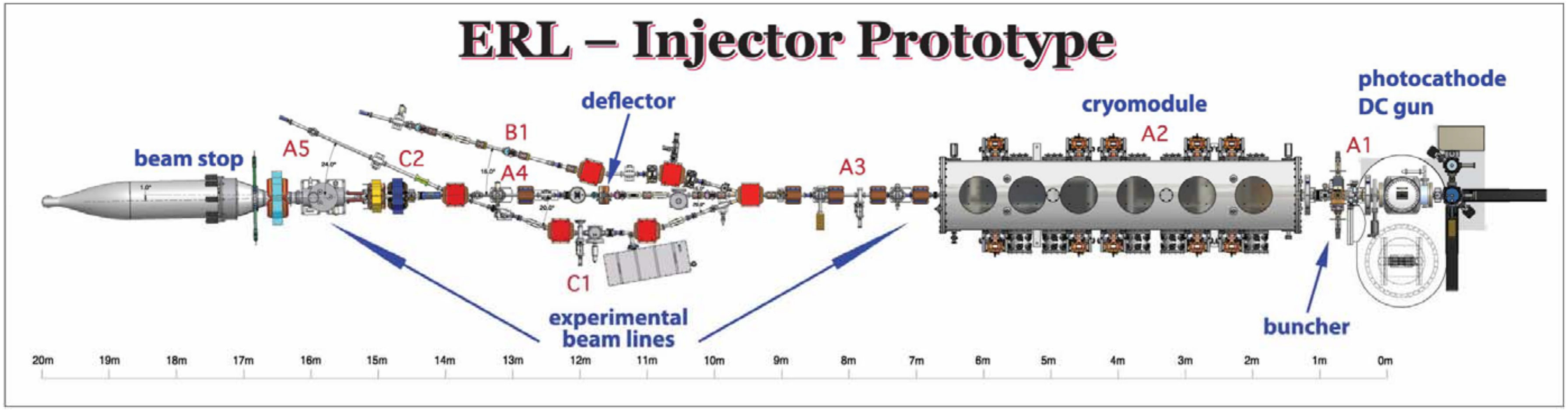
DC-Gun

現状の到達点

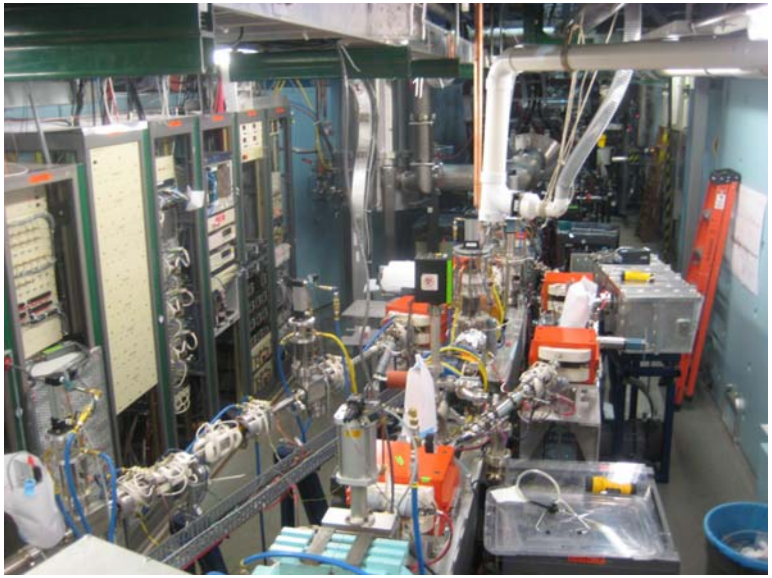
- Cornell – 350 kV, 8MeV, 65 mA,
  0.3 mm mrad @77 pC
- JAEA (1st Gun) – 500 kV, 1.8mA
- KEK (2nd Gun) – 480 kV (HV Conditioning)

我々の結果の報告については割愛します。

Cornell ERL Injector



Cornell: Bruce Dunham氏スライドより



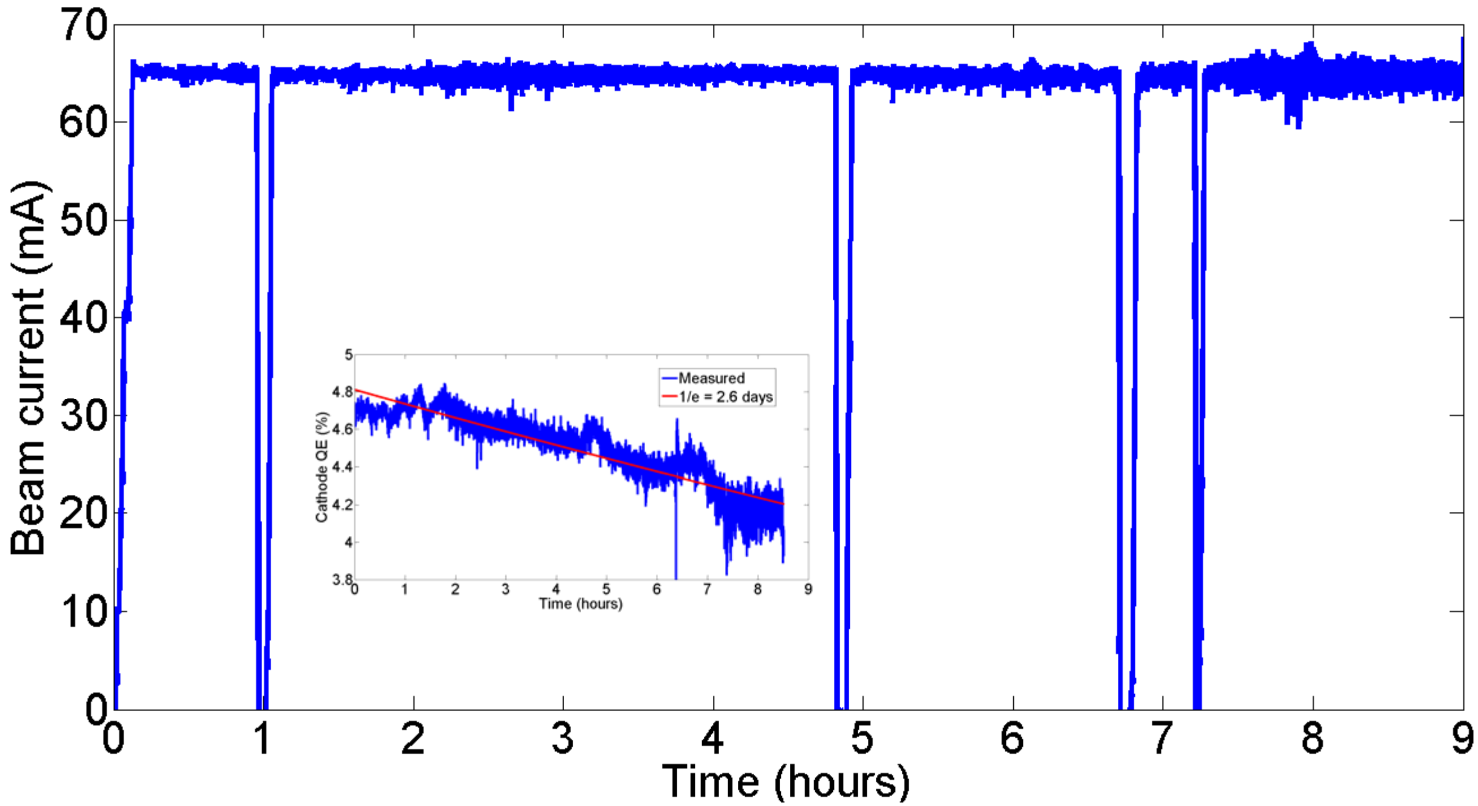
ERL Injector Prototype: Achievements to date:

- *75 mA average current @ 4 MeV*
- *0.3 µm emittance @ 77 pC, 8 MeV*

Injector Requirements

Parameter	Metric	Status	Notes
Average Current	100 mA		75 mA (1300 MHz)
Bunch Charge	77 pC		Pulsed mode (50 MHz)
Energy	5 to 15 MeV		14 MeV max (due to cryo limits)
Laser Power	> 20 W		> 60 W at 520 nm (1300 MHz)
Laser Shaping	beer can dist.		Adequate for now
Gun Voltage	500 kV		Currently operating at 350 kV
Emittance	< 2 μm (norm, rms)		Ultimate ERL goal 0.3 μm, with merger
Operational Lifetime	> 1 day		Recent improvements with new cathodes

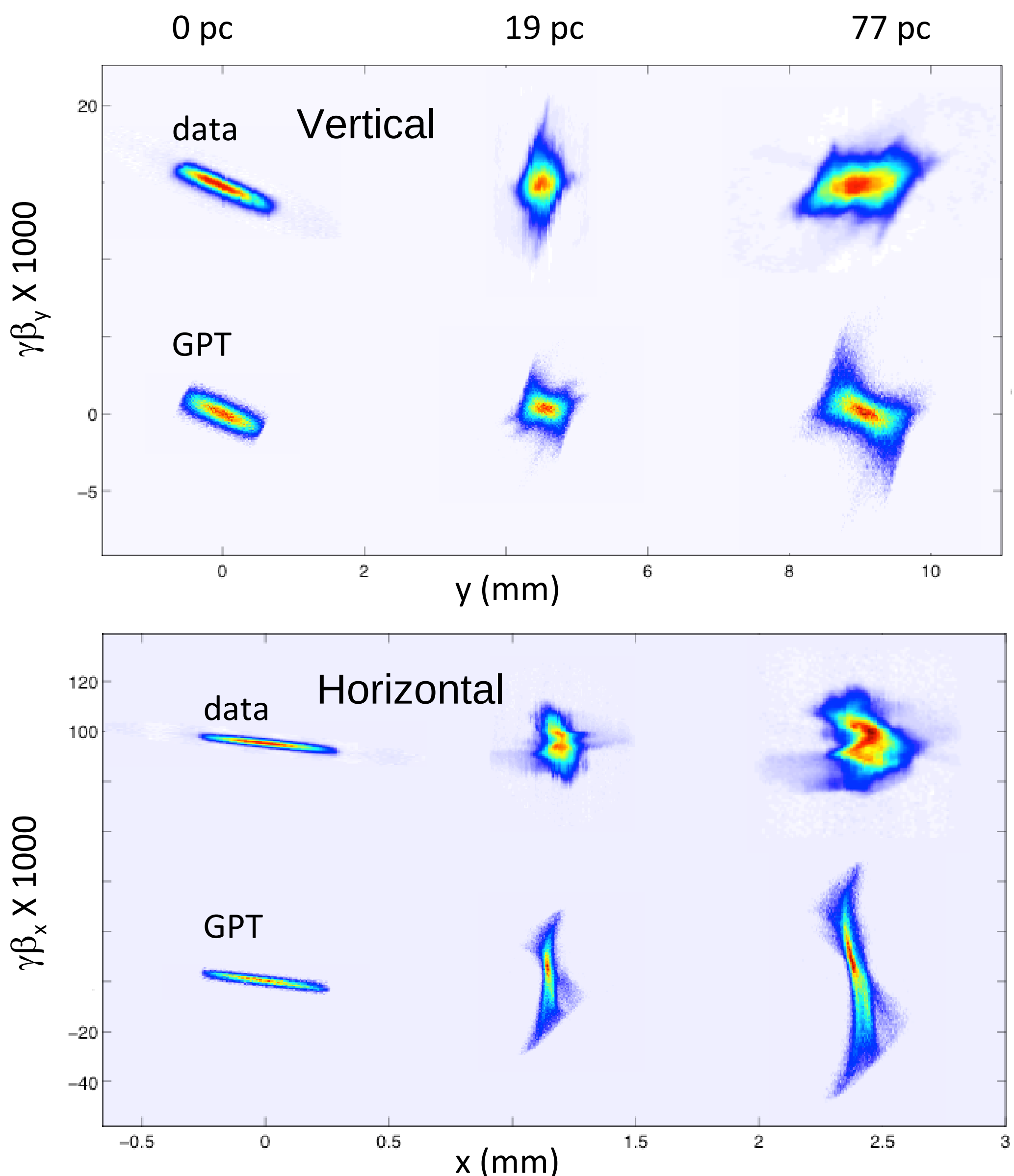
High Currents – Na_2KSb



Using a Na_2KSb photocathode, ran over 8 hours at 65 mA (2000 C) with a 2.6 day 1/e cathode lifetime. Reached as high as 75 mA for a short time.

*L. Cultrera, *et al*., *Appl. Phys. Lett*., 103, 103504 (2013)
*B. Dunham, *et al*., *Appl. Phys. Lett*., 102, 034105 (2013)

Emittance Results – Projected



Projected Emittance for 19 (77) pC @ 8MeV:

<u>Vertical Phase Space</u>

Data Type	en(100%) [microns]	en(90%) [microns]
Projected (EMS)	0.20(0.40)	0.14(0.29)
GPT	0.16(0.37)	0.11(0.25)

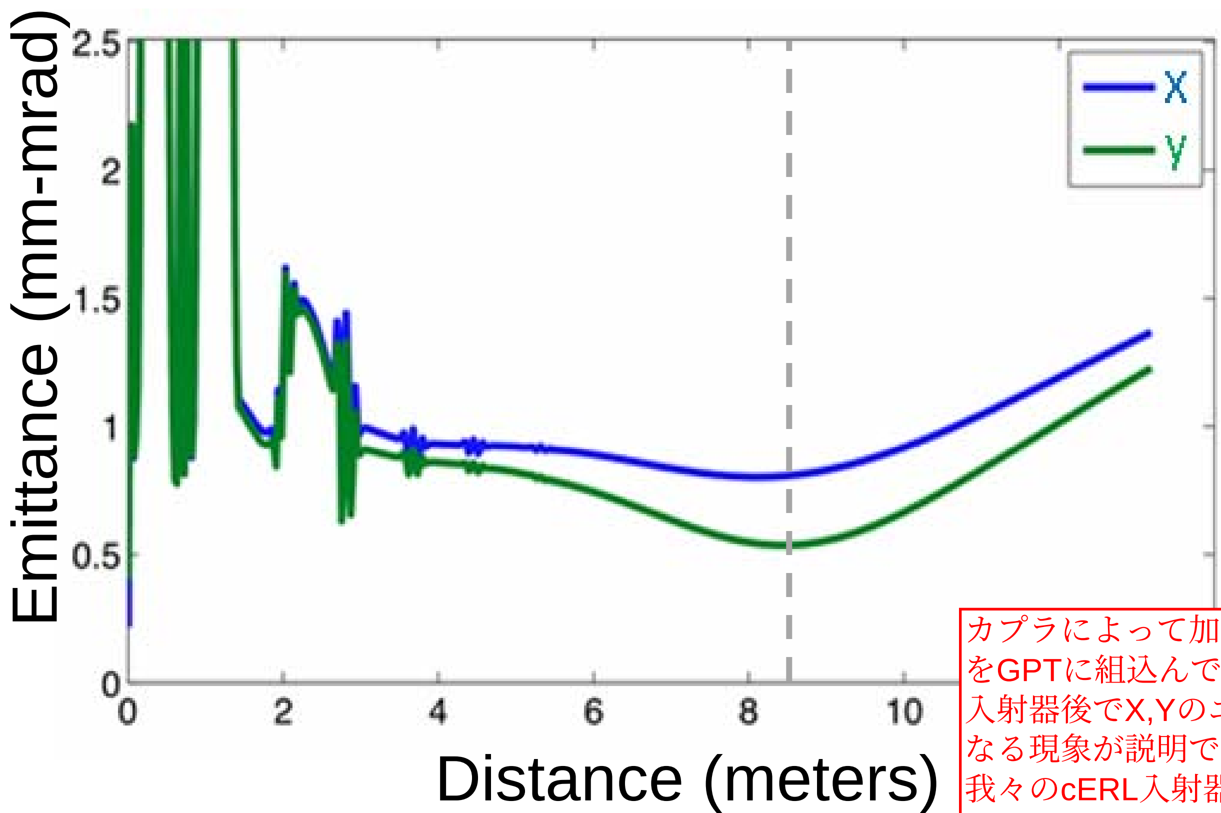
<u>Horizontal Phase Space</u>

Data Type	en(100%) [microns]	en(90%) [microns]
Projected (EMS)	0.33(0.69)	0.23(0.51)
GPT	0.31 (0.72)	0.19(0.44)

*C Guilliford, *et al*, PRST-AB **16**, 073401 (2013)

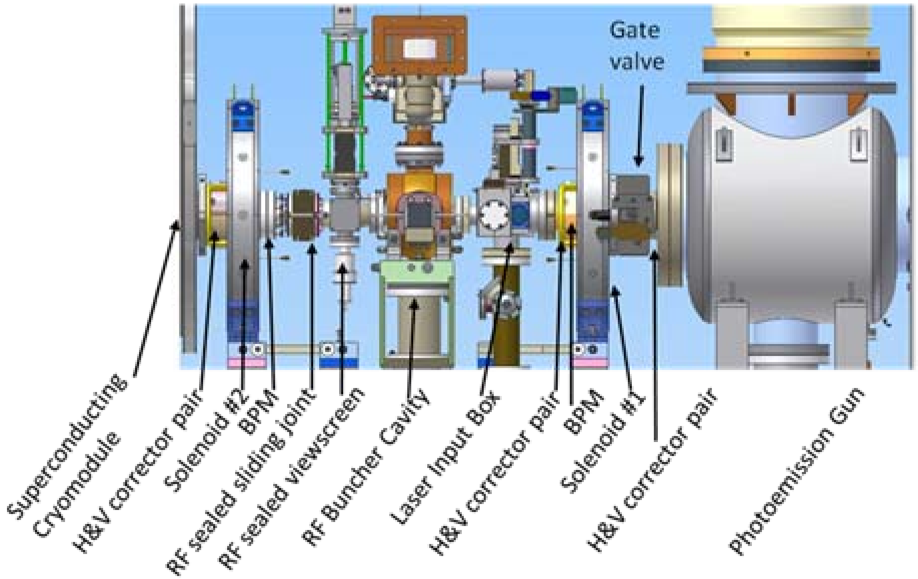
GPT Simulations

- Strong asymmetry after first cavity couplers
- Beam size asymmetry is accurately reproduced in the lab
- At minimum y emittance, the x emittance is 2x larger
- This is for a beam straight ahead (no merger)

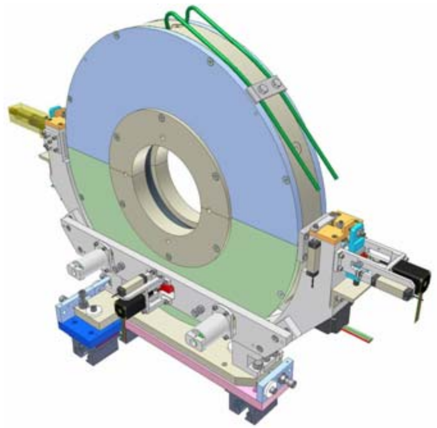


カプラによって加わる４極成分の電磁場をGPTに組込んでシミュレーション。
入射器後でX,Yのエミッタンスが非対称になる現象が説明できる。
我々のcERL入射器ではカプラが上下方向なのでXとYの関係が逆になる？

Alignment Accuracy



Aligning the magnetic and electrical centers of all elements to the beam axis is crucial for obtaining low emittance and minimizing aberrations.



Had to add remote control of the solenoids

Procedure:

1. Align laser at cathode center
2. Center on buncher using correctors (+/- 10 um)
3. Center on first 2 SRF cavities using correctors (+/- 10 um)
4. Center solenoid #1 by physical adjustments (+/- 50 um)
5. Center solenoid #2 by physical adjustments (+/- 50 um)

Lessons Learned

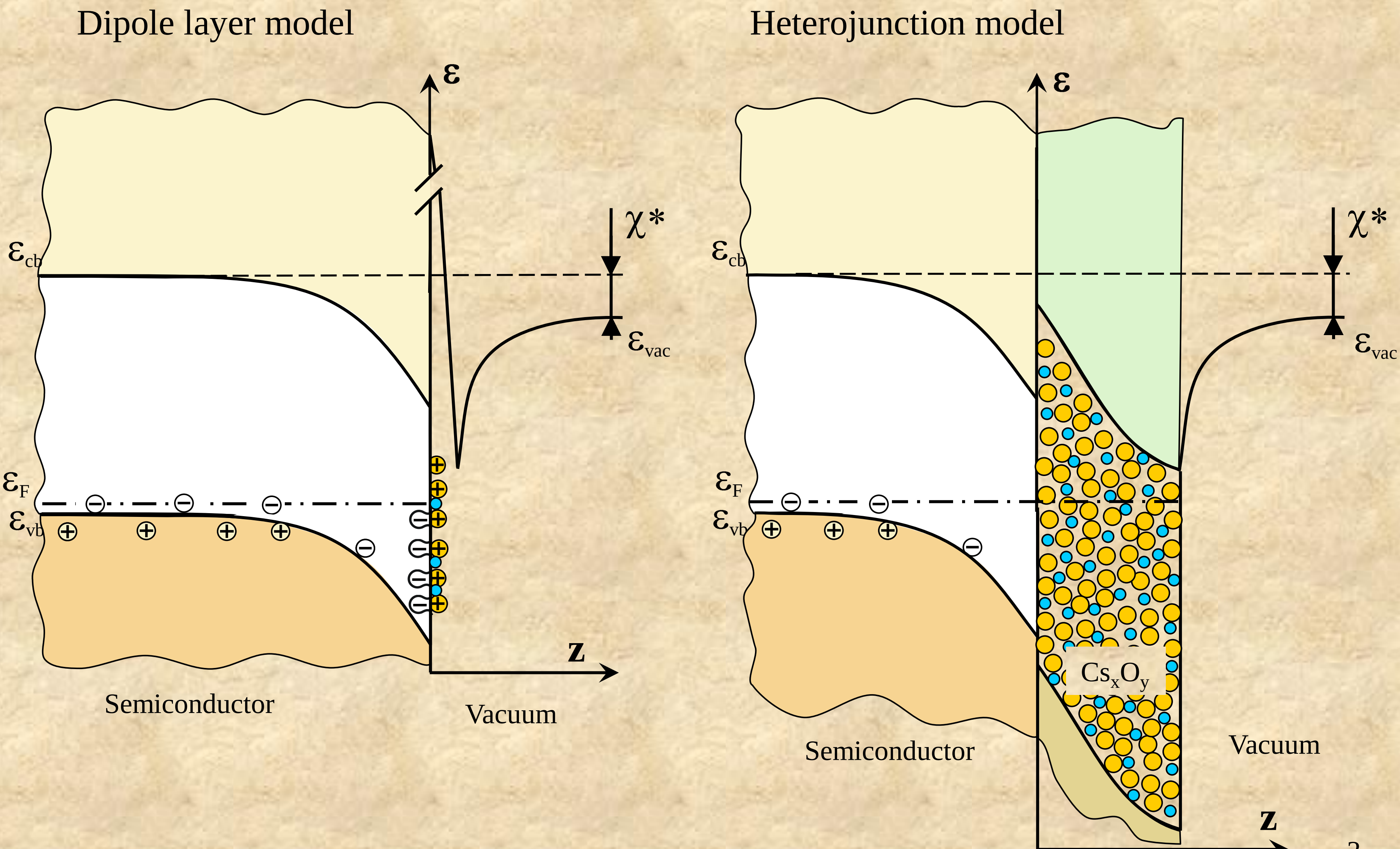
- High average currents with good lifetime from a photocathode are a reality
- Low emittance (near thermal) beams (with reasonable bunch charge) from a DC gun/SRF booster are a reality
- Extremely high DC voltages are not necessary to achieve our requirements (350 kV okay)
- Space charge simulations + genetic optimizations match experiments accurately
- Halo/beam loss can be maintained at or below 1 part in 10^7 to 10^8
- Cathodes are still the key for any photoemission gun

Photocathode

- BINP - NEA surface analysis
  MTE measurement

2. Actual models of (Cs,O)-activation layer.

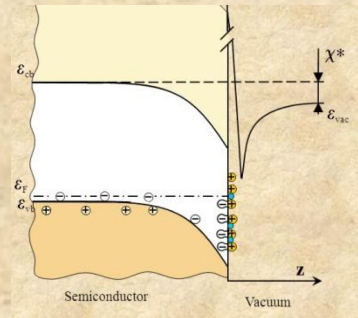
BINP(ISP): Aleksandr Terekhov氏スライドより



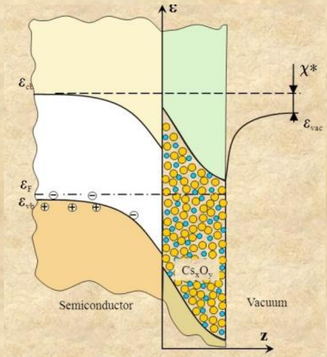
3. Photoelectron escape model.

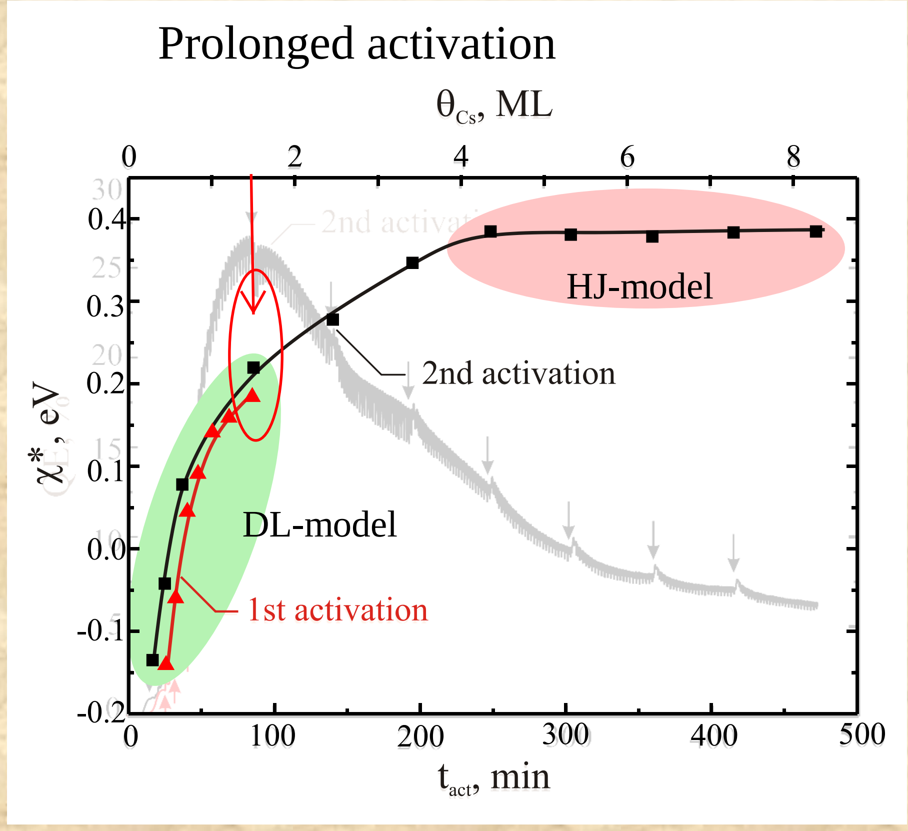
2. Actual models of (Cs,O)-activation layer.

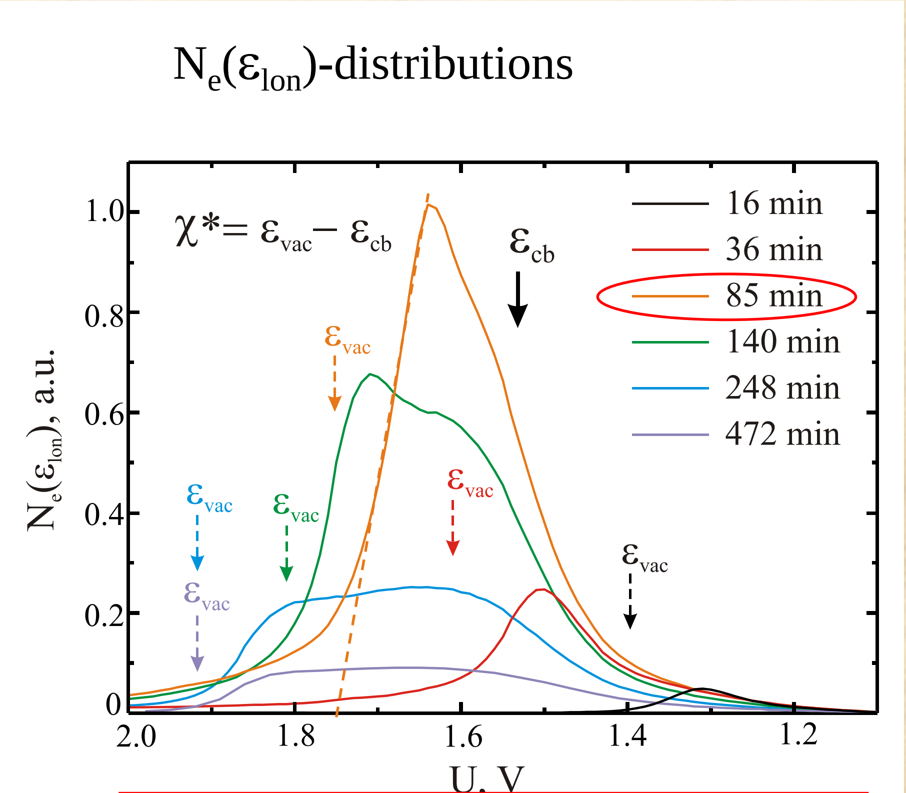
Dipole layer model



Heterojunction model



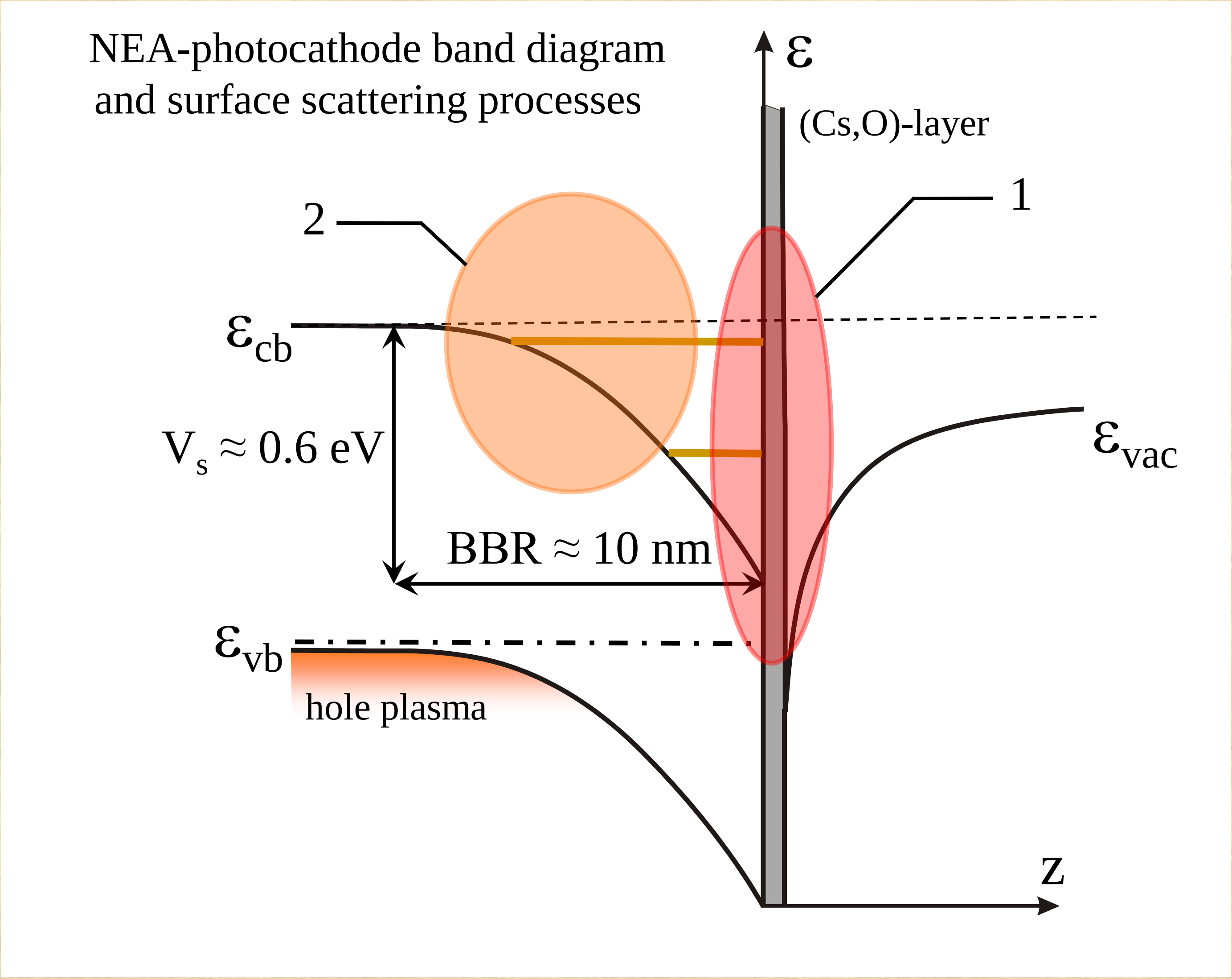




QEの波長依存性を励起エネルギーで微分すると得られるデータ。
弾道的に放出される電子エネルギーの位置から真空準位の位置がわかる

3. Photoelectron escape

3. Photoelectron escape model.

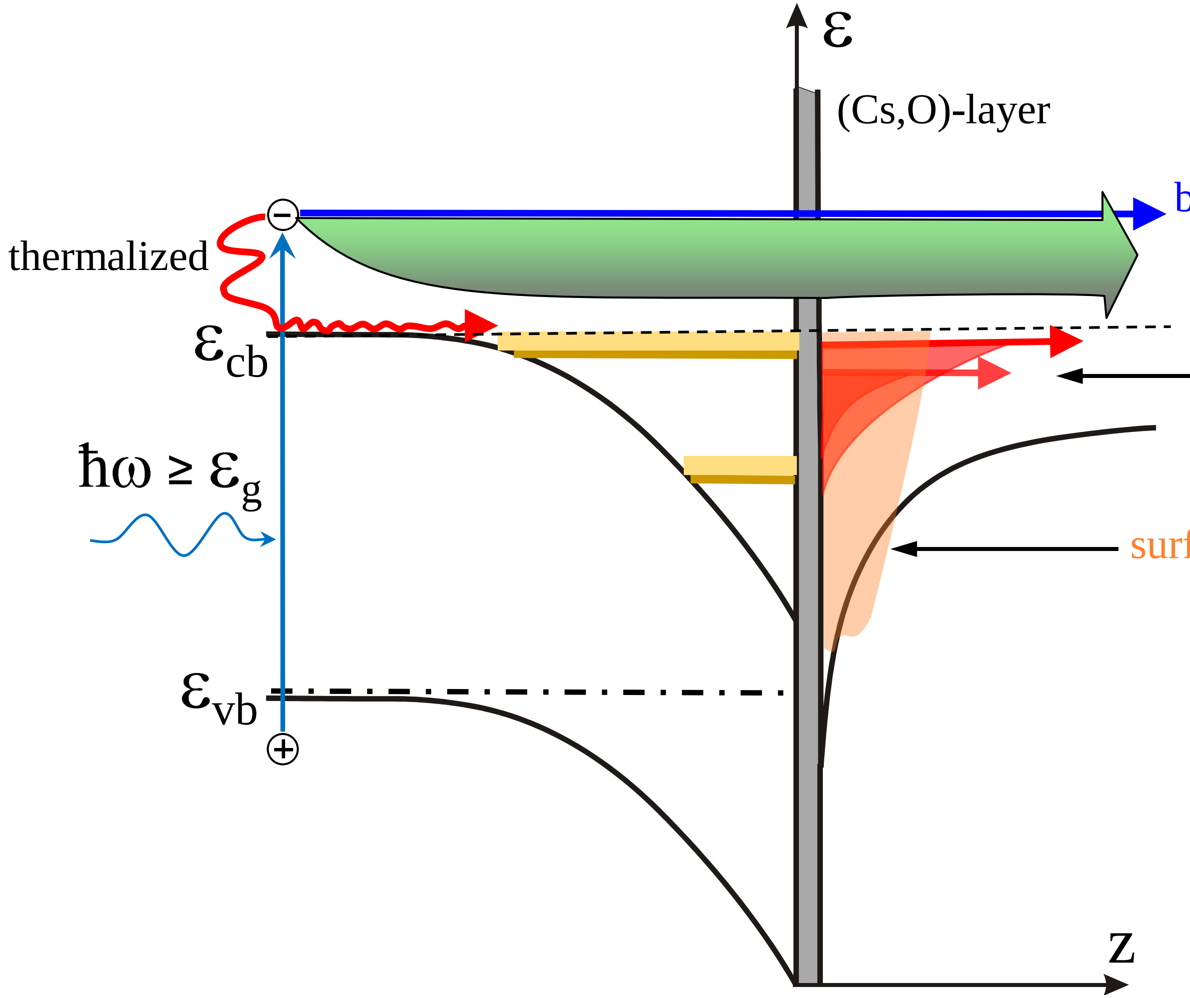


1. Surface optical phonons.
2. Surface plasmons.
3. BBR- induced random electric field.
4. (Cs,O)-induced random electric field.

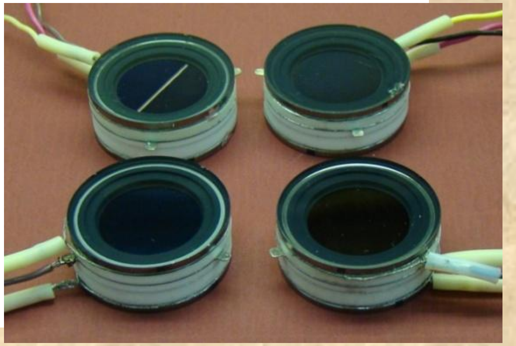
4. Parallel plate electron spectrometers.

3. Photoelectron escape model.

NEA-GaAsカソードでは、表面10nm程度のエリアで起こる現象で電子のエネルギー分布のほとんどが決まる。



spectrometers



4. Parallel plate electron spectrometers.

3. Photoelectron escape model.

Experiment

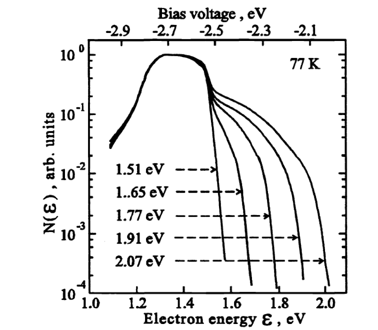


Fig.1 Electron distribution curves measured at various photon energies.

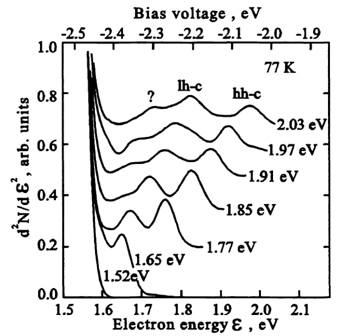


Fig.2 Secondary derivatives of the EDC at various photon energies.

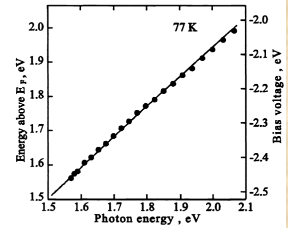
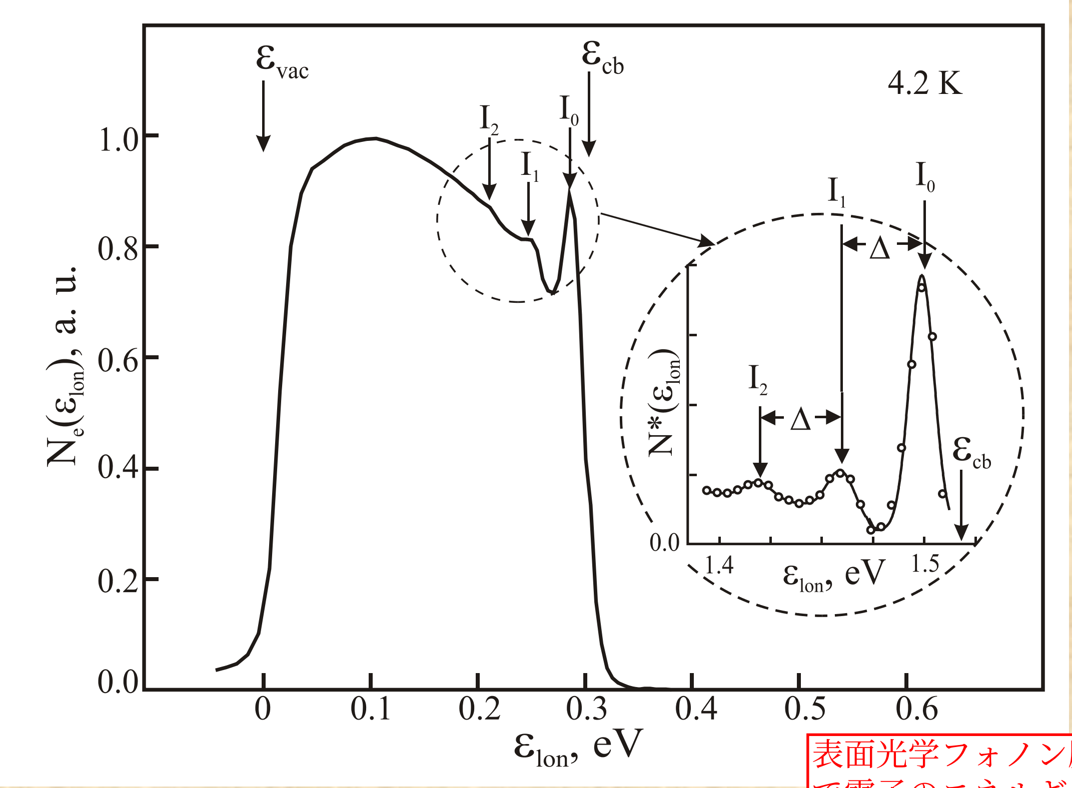


Fig.3 The measured (points, right scale) and calculated (solid line, left scale) energies of ballistic photoelectrons at different photon energies.



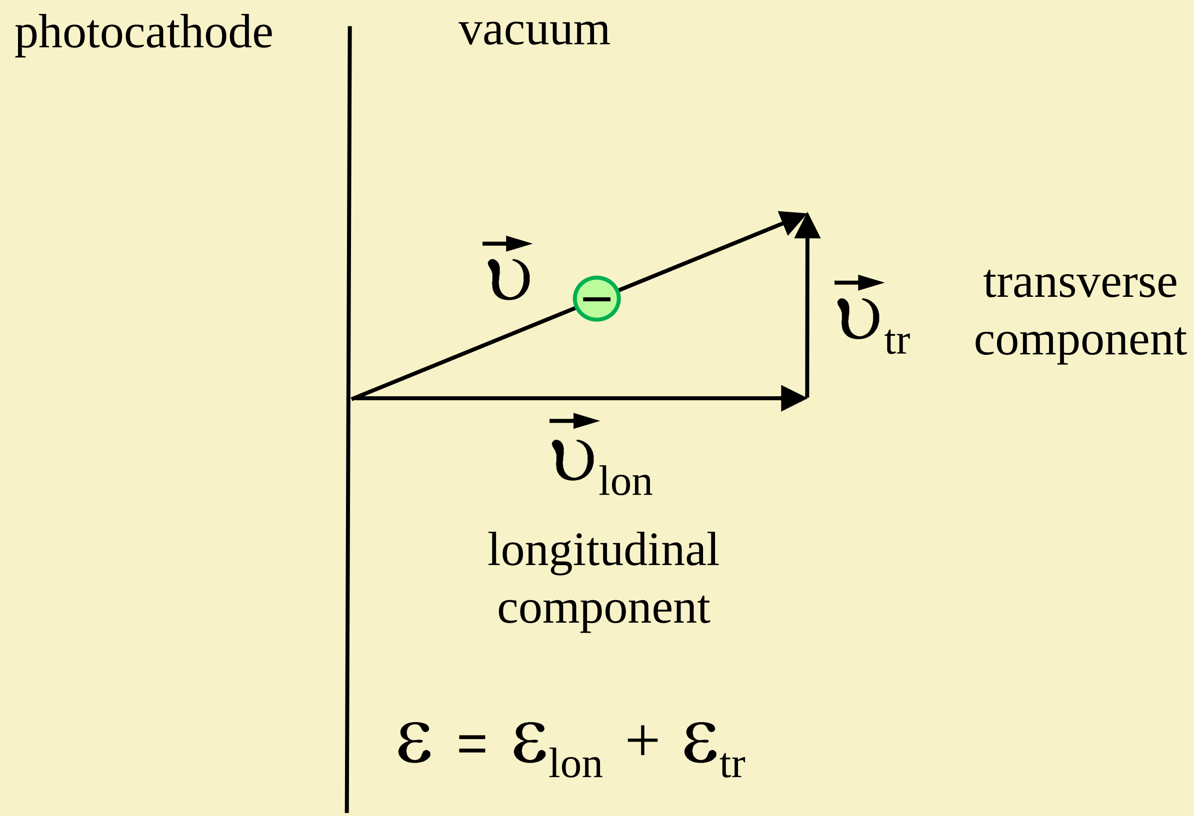
表面光学フォノン励起の影響で電子のエネルギー分布に特徴的なピークが見える。

D.A. Orlov et.al., JETP Letters v.71, p.220 (2000)

4. Parallel plate electron spectrometers.

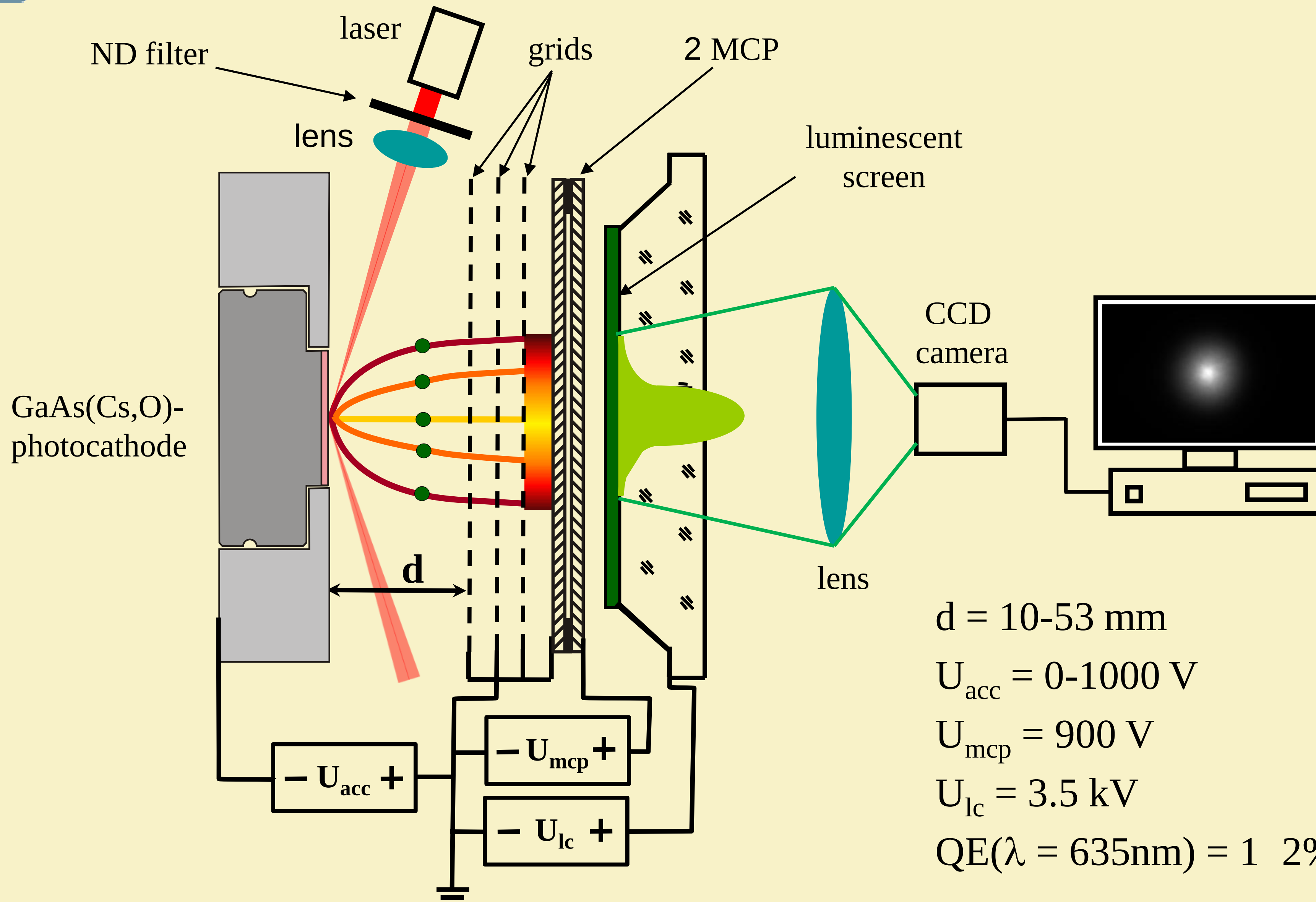
Principles of the technique

BINP(ISP):Heinrich Scheibler氏スライドより



$$\varepsilon = \varepsilon_{lon} + \varepsilon_{tr}$$

TESS measurements conditions



d = 10-53 mm

U_{acc} = 0-1000 V

U_{mcp} = 900 V

U_{lc} = 3.5 kV

QE(λ = 635nm) = 1 2%

Principles of the technique

Electron transit time from photocathode to MCP front surface τ is equal to

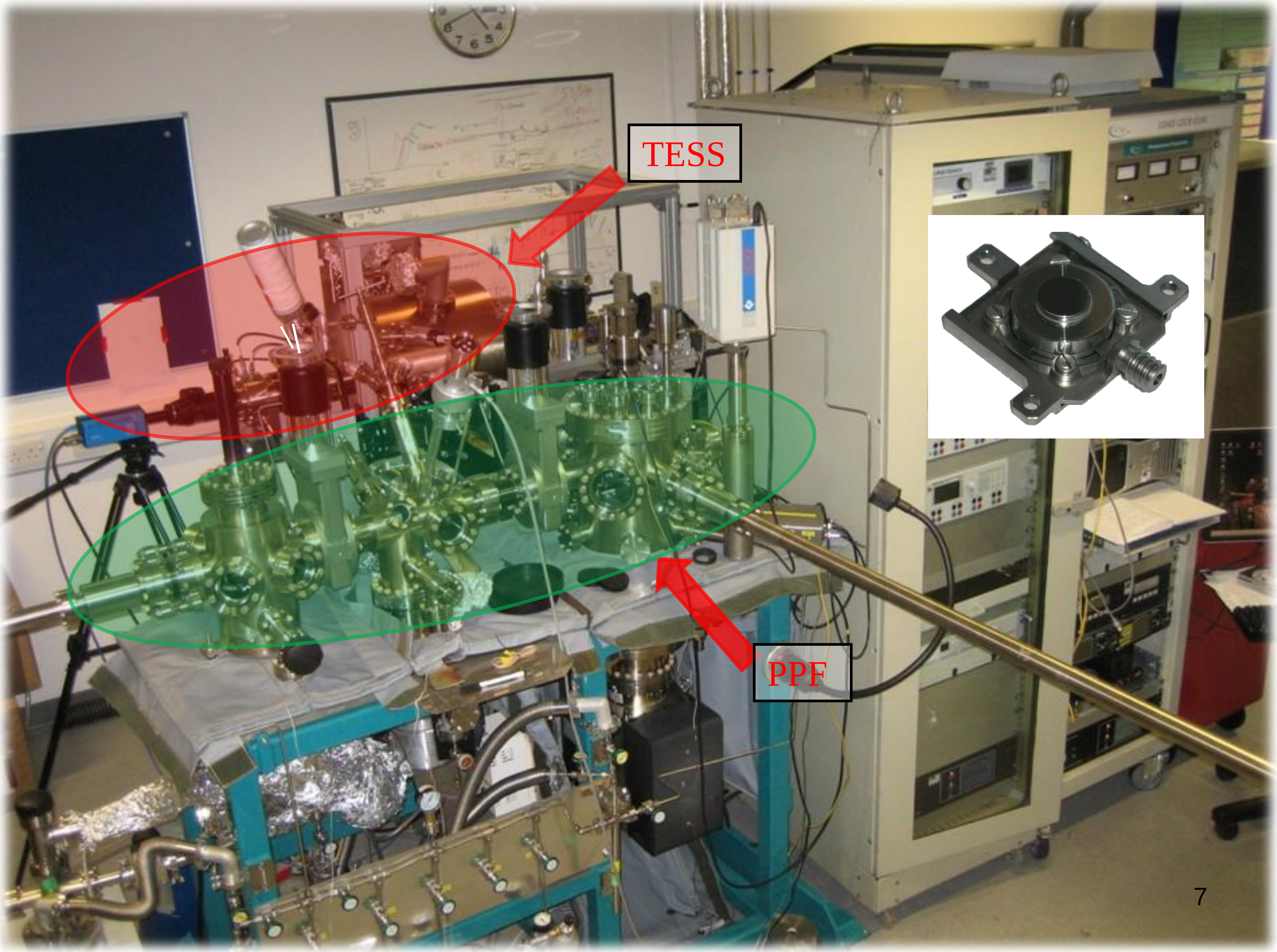
$$\tau = d \times \sqrt{\frac{2\,m_e}{e\,U_{acc}}} \times \left(\sqrt{1 + \frac{\varepsilon_{lon}}{e\,U_{acc}}} - \sqrt{\frac{\varepsilon_{lon}}{e\,U_{acc}}} \right)$$

e * Uacc >> Elon

where d – distance between photocathode and MCP, U_{acc} – accelerating voltage, applied between photocathode and MCP, ε_{lon} – longitudinal energy of the electron, m_e- free electron mass, e – electron charge.

In photocathode plane electron moves a distance r

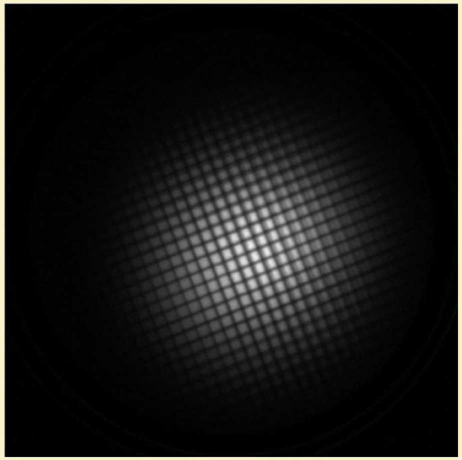
$$r = \sqrt{\frac{\varepsilon_{tr}}{2\,m_e}} \times \tau \qquad \text{and} \qquad \varepsilon_{tr} = \frac{m_e r^2}{2\,\tau^2}$$


TESS
PPF

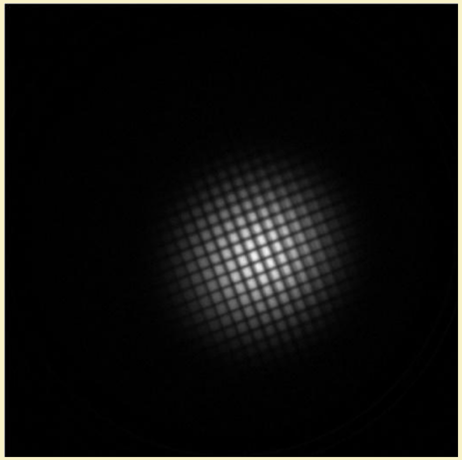
TEDC measurements with different light wavelength

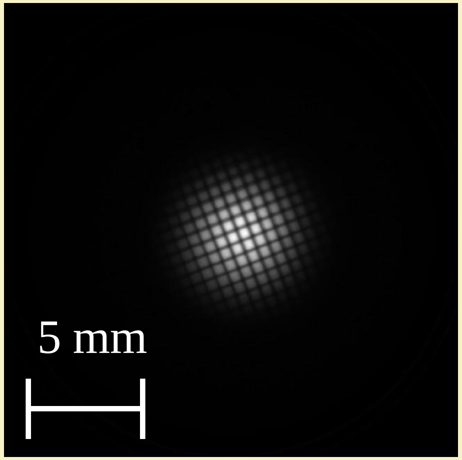
21.06.2013 p-GaAs(Cs,O) photocathode d ≈ 43 mm T = 300 K

λ = 532 nm | λ = 635 nm

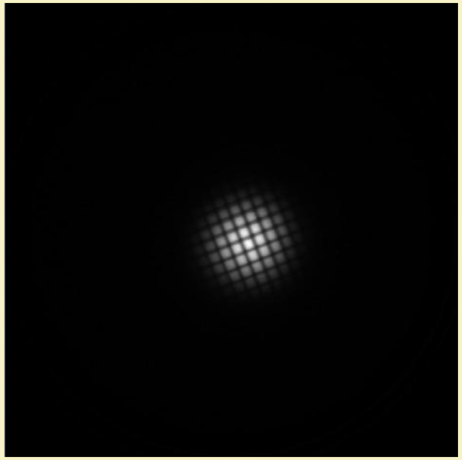


U_{acc} = 60 V





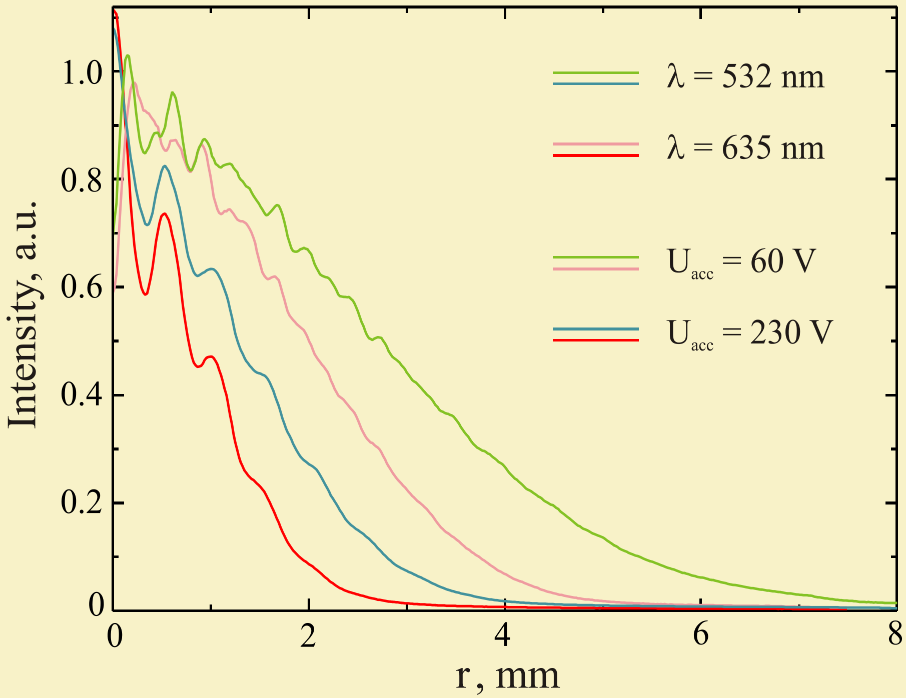
U_{acc} = 230 V



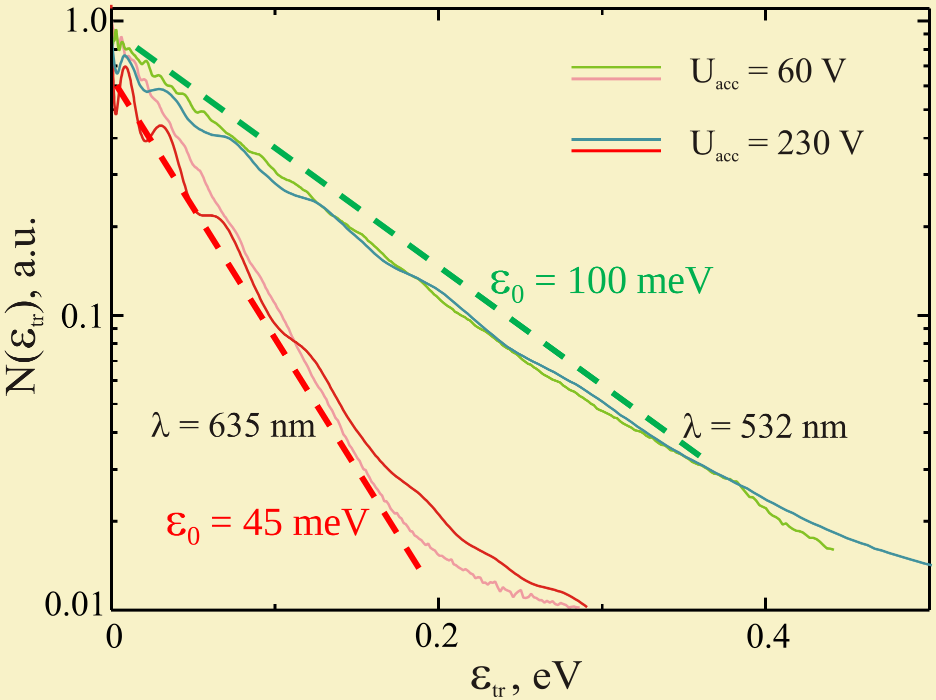
TEDC measurements with different light wavelength

21.06.2013 p-GaAs(Cs,O) photocathode d ≈ 43 mm T = 300 K

Screen luminescence profiles



Transverse energy distribution curves



MTE_{635}=45±7 meV MTE_{532}=100±15 meV

まとめ

- 100mA ERLがかなり現実味を帯びてきた。（Cornell大の成果）
  - Na_2KSbカソードの寿命 ~2000 Coulomb (=65mAで2.6日）
  - 65mAで8時間以上運転のdemonstration
  - $\varepsilon_{n.90\%}$ ~ 0.3 mm mrad @77 pC （Gun voltage: 350 kV)

- SRF-Gun開発の現状は、
  - HZDRでIR-FEL発振。（20pC, 13MHz, 2msで1.25Hzのmacro pulse）
  - まだ暗電流の影響が大きい。(HZDR,HZB)
  - カソードプラグ、電子銃空洞の構造のupgradeが進行中。
  - HZB,HZDR（の他DESY Flash等）のLaser systemはMBIが開発協力。
  - 100kW以上のCW大電力試験が始まった。(BNL)

- カソード開発・評価
  - 表面物性とMTE・カソード寿命の関係の究明
    結晶構造、結合状態、相互作用、表面粗さ、、、