Laser & Photocathode study for e-gun

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Outline - Literature

1. Photocathodes today
   Photocathodes in the future
2. Injector
   - Normal conducting
   - Superconducting
3. Various Parameters
   - Current,
   - Current density,
   - Frequency,
   - Operating temperatures,
   - Accelerating gradient
4. Conclusions

LITTERATURE

1. An Engineering Guide to Photo-injectors, T. Rao and D. H. Dowell, Eds.
2. SwissFEL cathode load-lock system: https://www.researchgate.net/publication/281093830_SwissFEL_cathode_load-lock_system
3. Ultraviolet laser transverse profile shaping for improving x-ray free electron laser performance, S. Li, et al., PHYS. REV. ACC.&BEAMS 20, 080704 (2017)

Classification of the current Photocathodes

- **Electron emission**
  - Photocathodes
    - » Metal
    - » Amorphous semiconductor
    - » Crystalline semiconductors
- **Electron acceleration**
  - DC high voltage
  - Radiofrequency acceleration
    - » Normal conductive acceleration
    - » Superconductive acceleration
  - VHF field acceleration
    - » Normal conductive acceleration
    - » Superconductive acceleration

The gun photocathode preparation and exchange needs a **Load-Lock** system, as the cathode exchange takes too time without this.
The cathode surface gets contaminated in the atmosphere during installation, leading to unpredictable quantum efficiency (QE) fluctuations. This system leads to use of semiconductor cathodes like Cs_2Te

Types and Criteria of Photocathodes

Metals – low efficiency, good time response (prompt), resistant to contamination, need UV laser (Cu, Mg)

Semi-conductors – high efficiency, slower time response, sensitive to contamination, visible/IR lasers (GaAs, Cs_2Te, K_2CsSb,GaN)

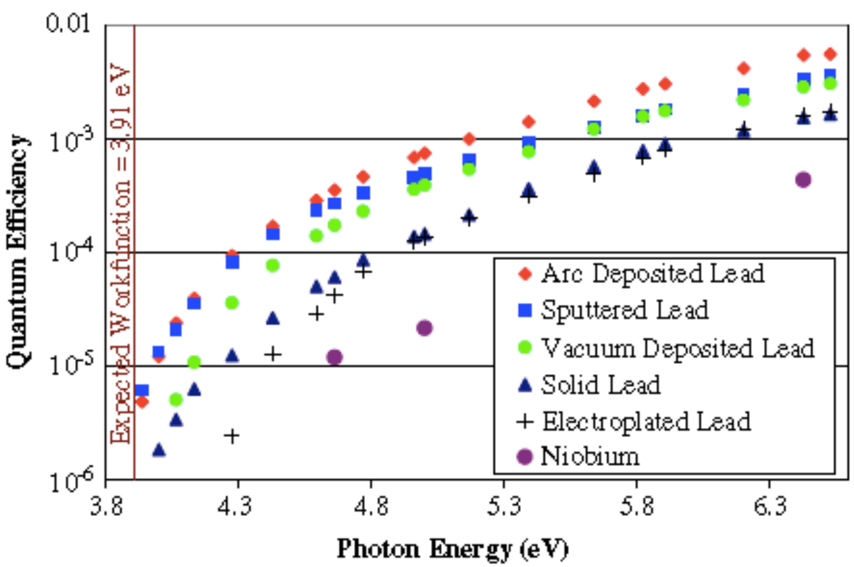
SELECTION CRITERIA

- High Quantum efficiency
- High Robustness
- Low intrinsic emittance
- Fast response time
- New ideas are welcomed!

Metal Photocathodes

- **Normal** conducting injectors
- **Room** temperature
- **Insensitivity** to contamination → easy handling
- **Longtime** operational lifetime, i.e. Mg, Cu are running for years
- **High work function**, ~1mA current :

  UV laser for driving
  High accelerating **gradient**
  Very little **dark current**
  QE quite law



QE of **Pb** deposited on **Nb** photo-cathodes.

The QE > 0.2% at 6.3 eV (196.3 nm) photon energy

It is proposed:

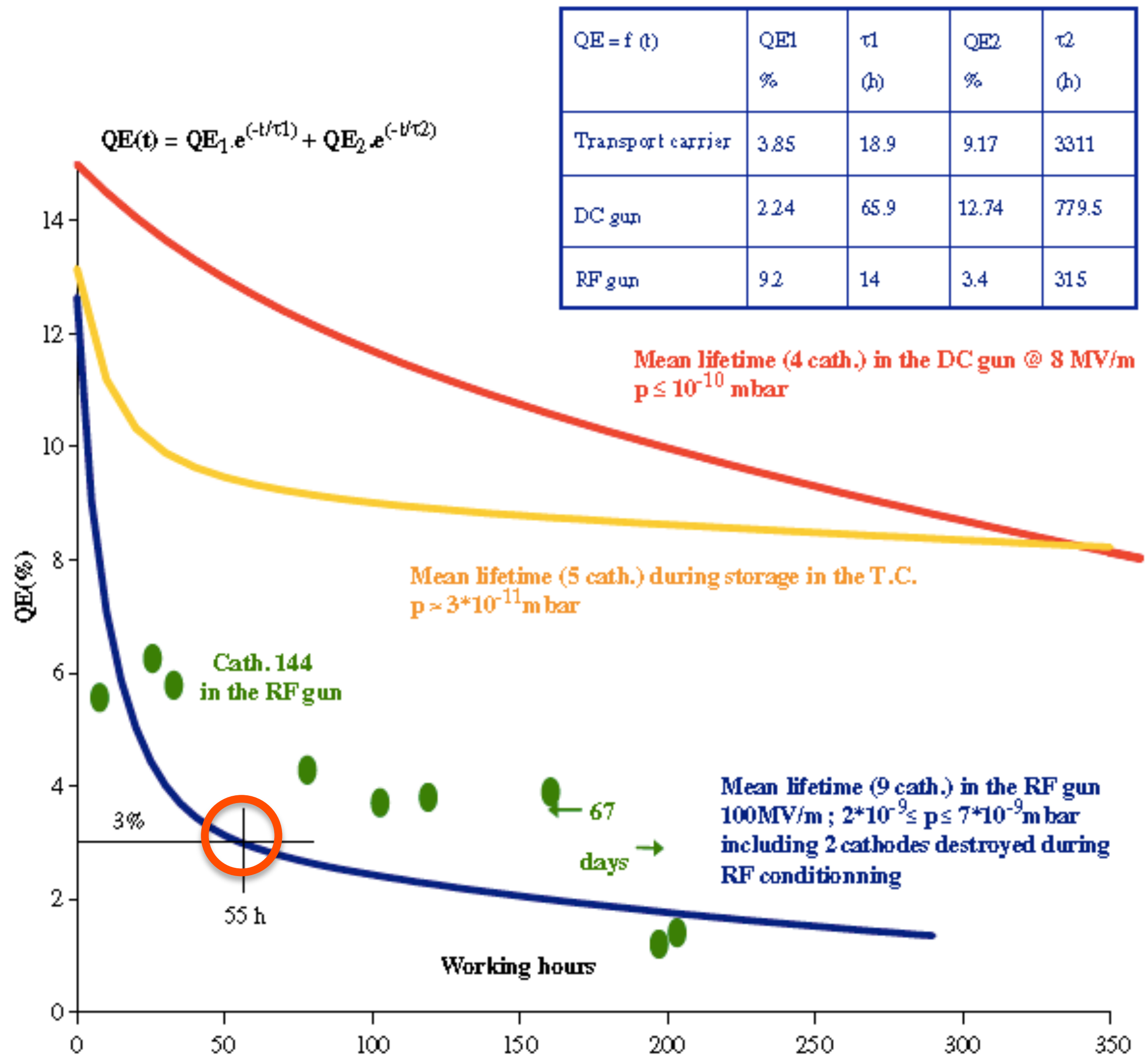
Mg → Normal conducting
Pb/Nb → Super-conducting

Cs_2Te Photocathodes, 10% QE at 266nm

- High QE in UV
- NC RF-injector
- High Acc. Gradient
- 4 nC/pulse delivered, ~1mA current
- High work function ➔ UV laser

- Sensitive to contaminants
- Quick QE decay from 12% to 3% in 55 h
- Load-lock system for cathode transfer/ exchange
- Evaporation CsBr on Cs_2Te improves the lifetime

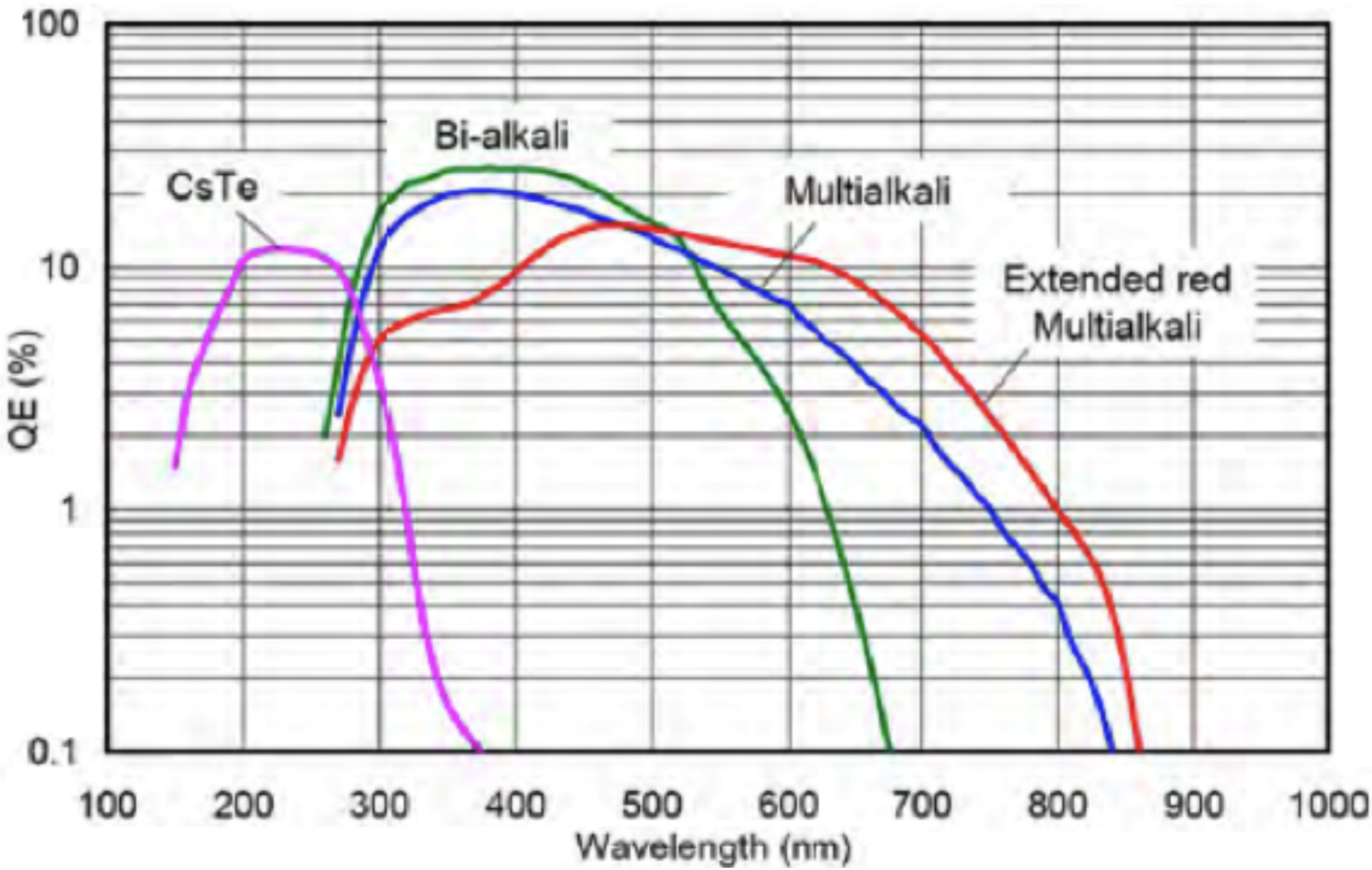
T. Rao et al. / Nuclear Instruments and Methods in Physics Research A 557 (2006) 124 130



Photocathodes

Cathode Wavelength	λ [nm] , E_{ph} [eV]	QE [%]	$E_a + E_{gap}$ [eV]	Thermal emittance $\left[\frac{\text{mm mrad}}{\text{mm rms}}\right]$	
				Theory (Equ. 7.6)	Experiment
Cs_2Te	262, 4.73	~10	3.5	0.9	1.2 ± 0.1
Cs_3Sb	532, 2.33 473, 2.62 405, 3.06	~4 ~7 ~9	1.6 + 0.45	0.42 0.62 0.82	0.56 ± 0.03 0.66 ± 0.03 0.80 ± 0.04
Na_2KSb	330, 3.76	~10	1 + 1	1.07	N/A
Na_2KSb:Cs	390, 3.18	~20	1 + 0.55	1.03	N/A
K_2CsSb	532, 2.33 473, 2.62 405, 3.06	~4 ~11 ~25	1 + 1.1	0.38 0.58 0.80	0.56 ± 0.03 0.69 ± 0.03 0.87 ± 0.04
GaAs(Cs,F)	532, 2.33	~10	1.4 ± 0.1	0.77	0.47 ± 0.03
GaN(Cs)	260, 4.77	~15	3.4 ± 0.1	0.94	1.35 ± 0.11

Photocathodes



Summary of Photocathodes

Class	Material	QE	Response time	Intrinsic Energy	Wave Length	Gun	Application
Normally conducting metals	Cu, Mg	10^{-5}-10^{-4}	10's fs	100's mV – 1's V	UV	NC-RF, VHF	Low rep rate FELs
Super conducting metals	Nb, Pb	10^{-5}-10^{-4}	10's fs	100's mV – 1's V	UV	SC-RF	High rep rate FELs
Positive e^- affinity Te-based	Cs_2Te	0.1-0.2	ps's	100's mV	UV	NC-RF, SC-RF VHF DC	High rep rate FELs
Positive e^- affinity Sb-based	Cs_3Sb etc	0.1-0.2	ps's	100's mV	Visible	DC VHF, SCRF(?) NCRF(???)	ERLs, High rep rate FELs
Negative e^- affinity semiconductor	GaAs, etc	0.1-0.35	1 – 100 ps	10's mV – 100's mV	IR- Visible	DC (XHV)	Polarized sources, ERLs

Lasers

The **laser** system for the photo-injector is selected based on the **cathode material** and the **electron beam parameters** required for the application

The **temporal** and **transverse shape** of the laser pulse, together with the **quantum efficiency (QE)** of the photocathode surface, determines the temporal and transverse distribution of the electron beam upon emission; having a significant impact on beam brightness and FEL performance

Metal photocathodes require **UV photons** due to their high work function, therefore eliminating the use of liquid crystal SLMs (= Spatial Light Modulator) directly in this wavelength range

Host	Dopant	Wavelength [μm]	Band Width [nm]	Gain Cross Section [$\times 10^{-20}$ cm^2]	Upper State Lifetime [μs]
YAG	Nd	1.064	0.6	33	230
YLF	Nd	1.047-1.0530	1.2	18	480
Vanadate	Nd		0.8	300	100
Phosphate Glass	Nd	1.0535-1.054	24.3	4.5	323
KGW	Yb	1.026	25	2.8	250
YAG	Yb	1.030	6.3	2.0	950
Phosphate Glass	Yb	1.06-1.12	62	0.049	1 300
Sapphire	Ti	0.790	230	41	3.2

MAXIV laser→ Ti:Sapphire with specifications

Central wavelength	790 nm
Pulse duration	50 fs
Pulse energy	7.5 mJ
Repetition rate	1 kHz

The following parameters to be defined with codes ASTRA and DYNAC:

- ✓ The electron emission affection by the electron **beam space charge field**:

$$E_{SCL} = \frac{q}{A\varepsilon_0} = \frac{\sigma}{\varepsilon_0}$$

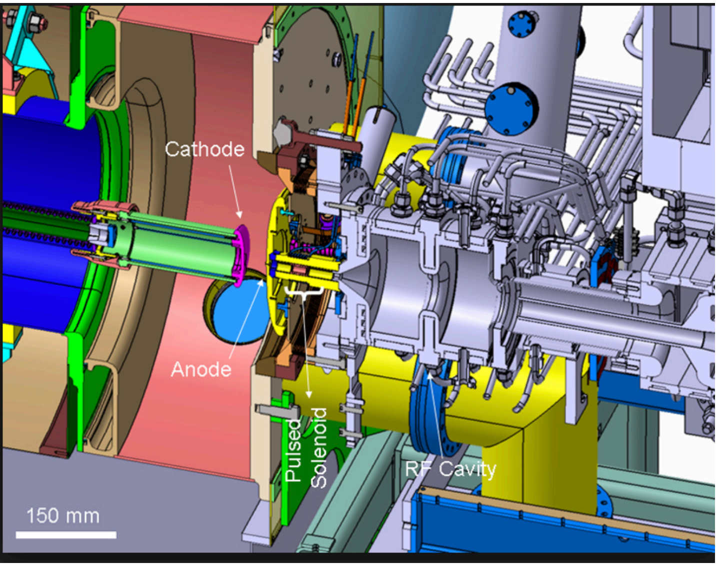
- ✓ The 2-D sub-spaces of *xx′*, *yy′* and *zz′*, the trace spaces,
- ✓ The energy normalized trace space emittance:

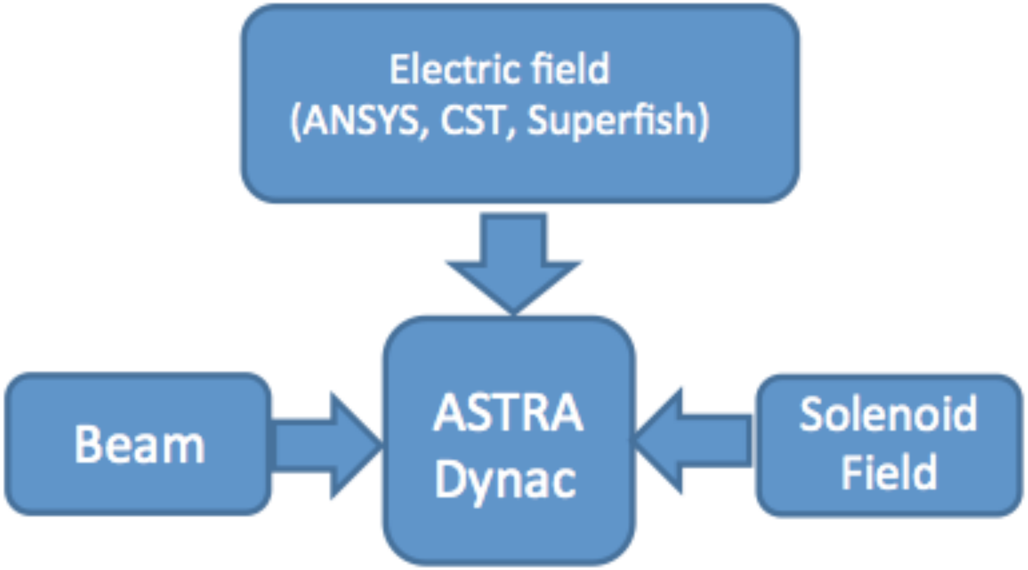
$$\varepsilon_n = \beta\gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

- ✓ The peak current, I_{peak}, as the bunch charge divided by the bunch length, at the FWHF of the bunch length
- ✓ The transverse normalized beam brightness combining the emittance and the peak current:

$$B_n = \frac{2I}{\pi^2 \varepsilon_{n,x} \varepsilon_{n,y}}$$

e-gun Simulation & Strategy for INFN/SWISS FEL



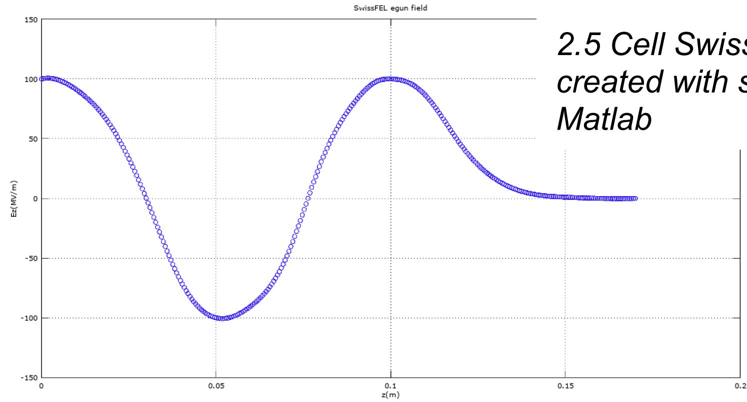


Material:

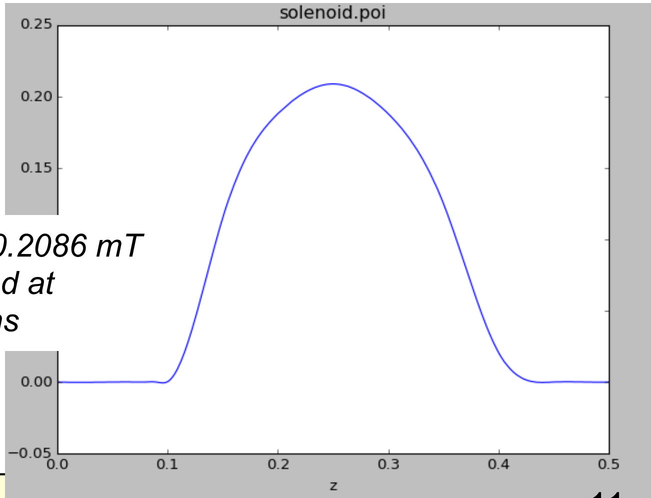
Beams: INFN Beam, SwissFEL Beam (NTUA team)

Electric Fields: 1.5 cells (INFN) , 2.5 cells (SwissFEL) created with Matlab

Solenoids: INFN, SwissFEL created with Matlab



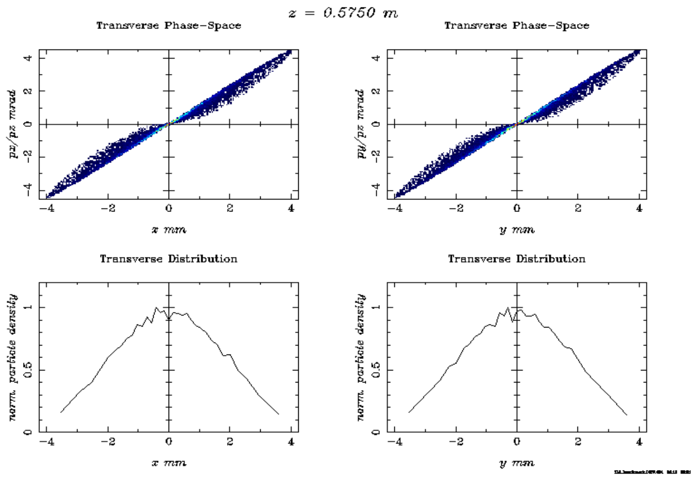
2.5 Cell SwissFEL Gun Electric field created with spline interpolation on Matlab

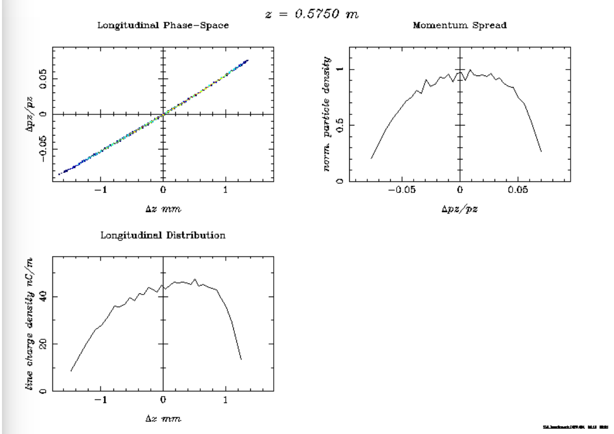


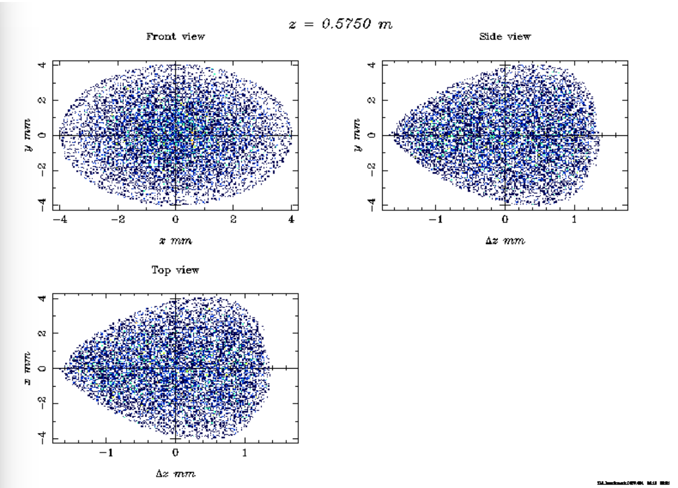
Different Solenoids with peaks at 0.2086 mT like SwissFEL gun solenoid created at Matlab and used for the simulations

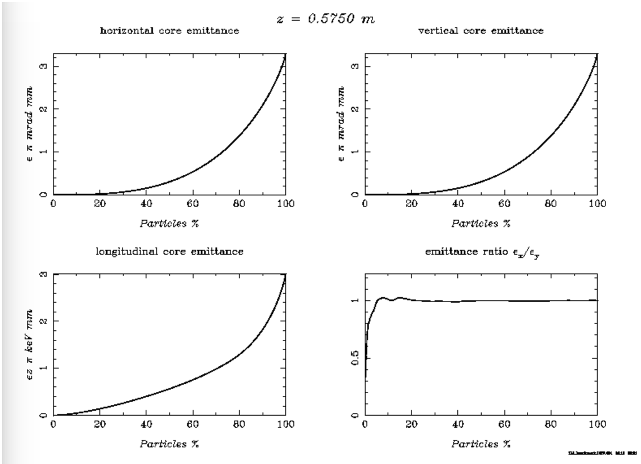
Preliminary simulating data by ASTRA

Scenario I : INFN Beam , 1.5 cell, INFN Solenoid
Scenario II:INFN BEAM, 2.5 Cell- SwissFEL , INFN solenoid
Scenario III: INFN Beam- 2.5 cell RF gun SwissFEL , created solenoid
Scenario IV- INFN Beam, 2.5 Cell RF gun SwissFEL – created solenoid shifted 0.1m

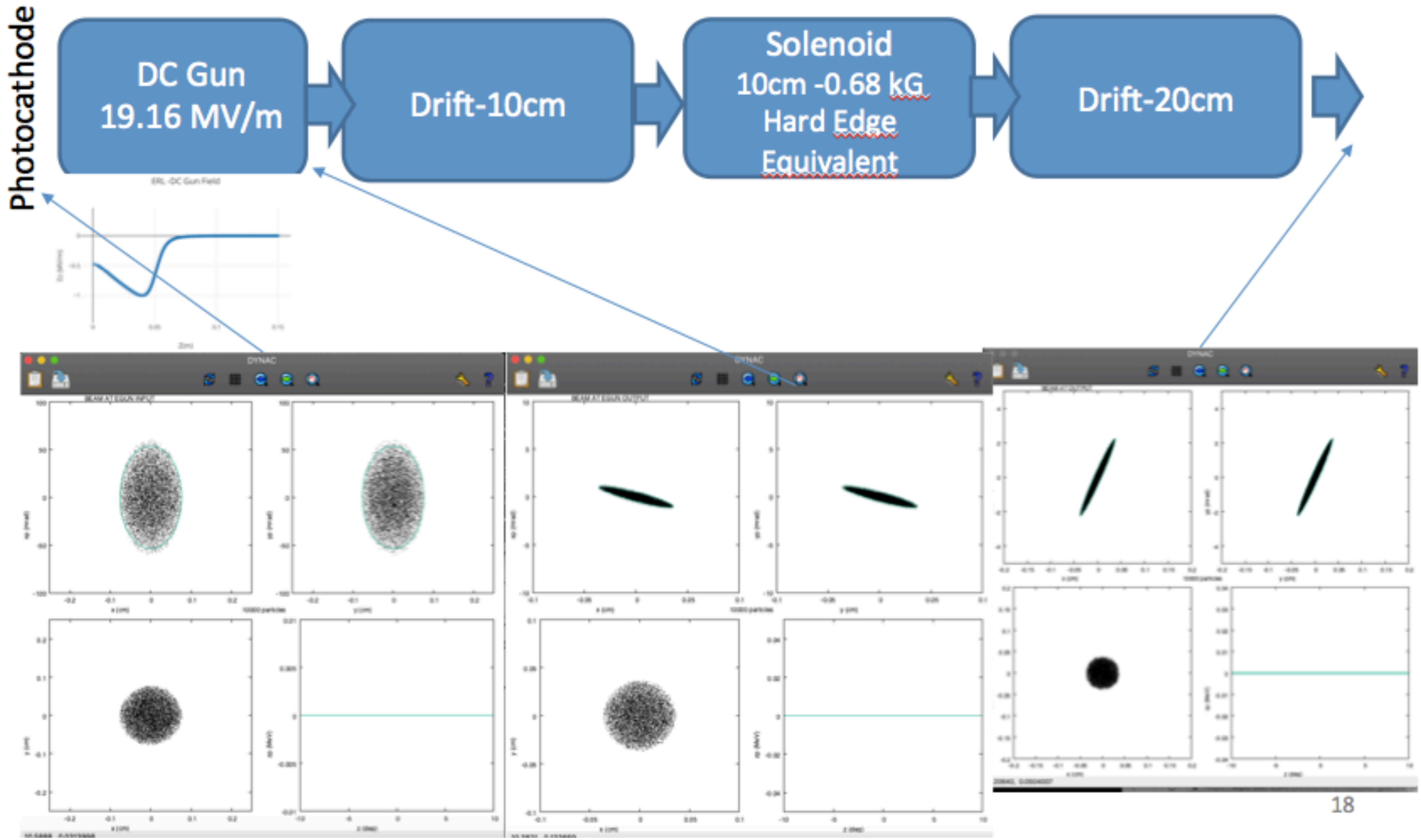








Preliminary simulating data by DYNAC for ERL DC gun



Conclusions

- Various **modes** and **types** of the photocathodes have been investigated
- The choice of the photocathode is **dictated** by the requirements on the **average current** and by the **available laser**
- Reliable cathode and laser systems exist for average current of **10 mA**
- The current can be increased to **100 mA**, by a small improvement in both the cathode and the laser system
- The limited lifetime of the cathodes is an **IMPORTANT** issue
- An important study of the **the degradation** of the cathode performance, so to improve **the lifetime** of these cathodes at least by an order of magnitude is necessary
- A very very preliminary proposal could be :

a cathode Cs_2Te, with **QE ~0.1-0.2 %, UV, SC/NC-RF, High repetition rate; by a UV laser**

But … More study is needed for final selection

Conclusions cont' ed

- ASTRA and DYNAC codes were investigated for simulation of the beam after the Photocathode.
- Preliminary results were presented
- Simulation methodology and strategy have been established

The IASA-NTUA-ESS team will work to:

- **Simulations** with respect to proposed topologies for:
  - ✓ Electron generation by laser
  - ✓ Beams from photocathode and perform structure optimization

- **Mechanical designs** of the photocathode, RF cavity and Solenoids

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