
WIR SCHAFFEN WISSEN – HEUTE FÜR MORGEN

Simona Bettoni with inputs from many people :: SwissFEL :: Paul Scherrer Institut

Ultra low emittance injector for Porthos

Brainstorming meeting – 28th January 2022

PAUL SCHERRER INSTITUT


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~~Ultra low emittance~~ injector for Porthos Best performance

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Outlook

- **Goal**

- **Present situation at SwissFEL and impact of an improved beam**

- **Rf guns developments:**
  - Normal conducting C-band rf guns (INFN, PSI)
  - Cryo-cooled rf guns (UCLA, SLAC, INFN)

- **Cathodes developments:**
  - Where we are
  - Possible improvements

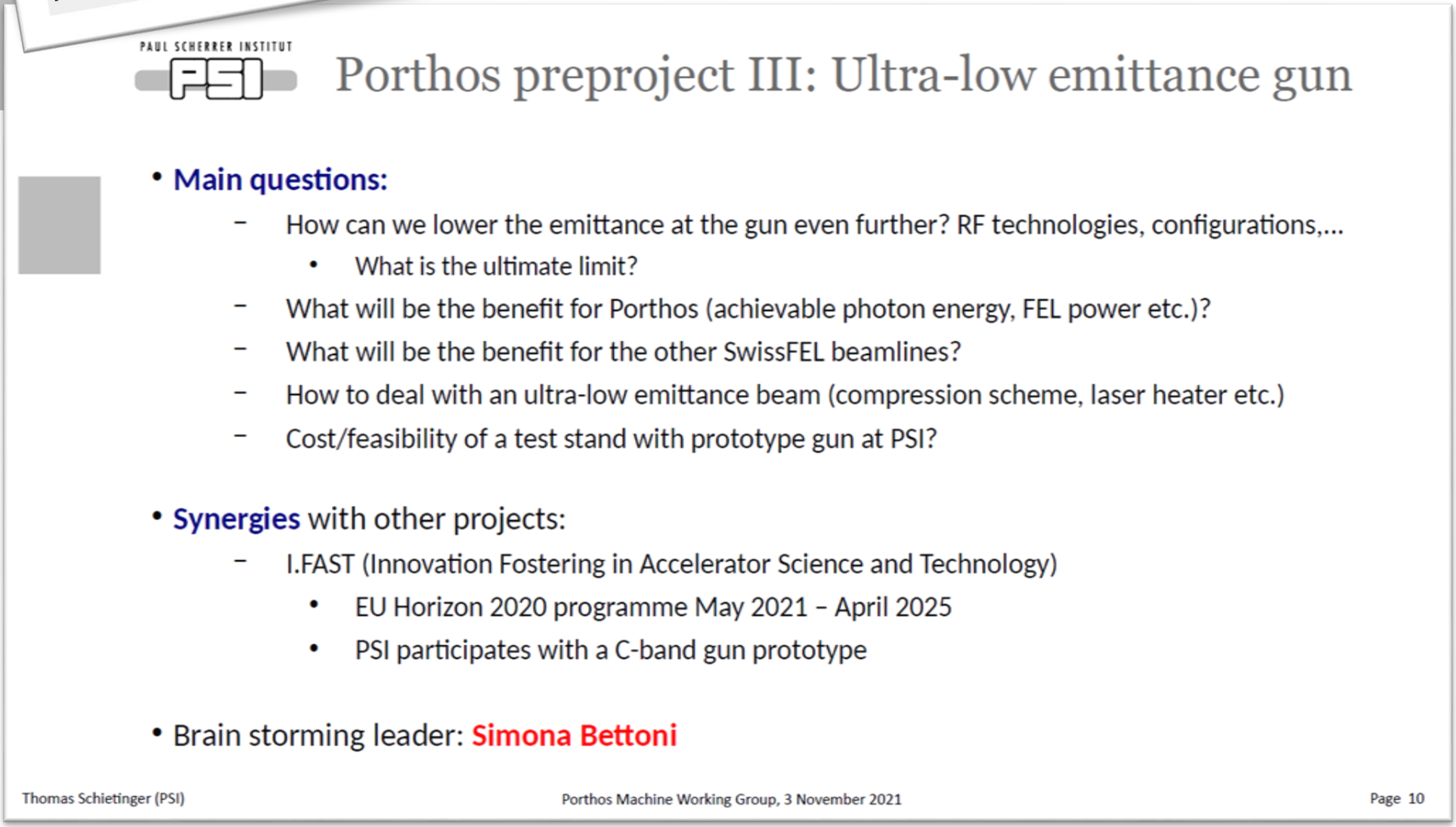
- **More on the the injector performance optimization**

- **Measurements plans:**
  - What to measure
  - How to measure
  - Where to measure

- **Discussions**

Goal

From the Thomas' previous presentation



Porthos preproject III: Ultra-low emittance gun

- **Main questions:**
  - How can we lower the emittance at the gun even further? RF technologies, configurations,...
    - What is the ultimate limit?
  - What will be the benefit for Porthos (achievable photon energy, FEL power etc.)?
  - What will be the benefit for the other SwissFEL beamlines?
  - How to deal with an ultra-low emittance beam (compression scheme, laser heater etc.)
  - Cost/feasibility of a test stand with prototype gun at PSI?
- **Synergies** with other projects:
  - I.FAST (Innovation Fostering in Accelerator Science and Technology)
    - EU Horizon 2020 programme May 2021 – April 2025
    - PSI participates with a C-band gun prototype
- Brain storming leader: **Simona Bettoni**

Thomas Schietinger (PSI)

Porthos Machine Working Group, 3 November 2021

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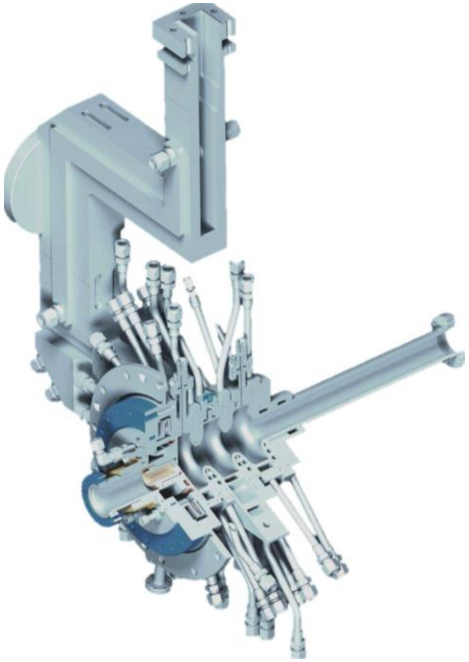
Present SwissFEL gun

RF design J. Y. Raguin, et al.

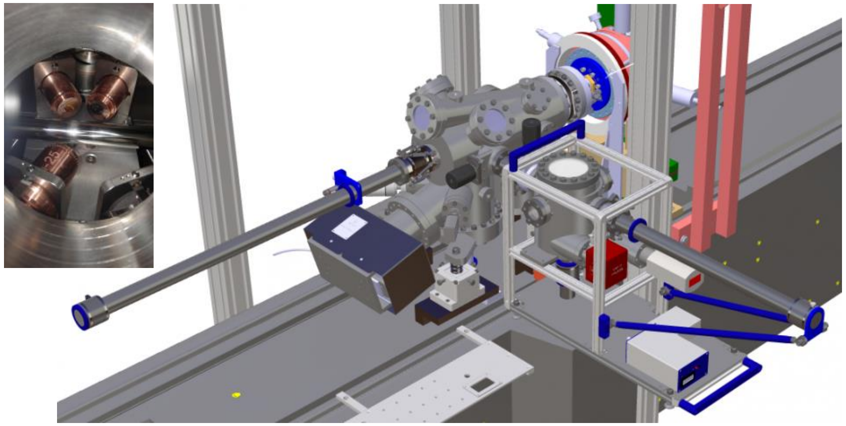


SwissFEL rf gun:

- S band, 2.5 Cell
- Final total beam energy 7.1 MeV
- Standing wave
- **Maximum G** = 100 MV/m (76 MV/m at extraction)
- Repetition frequency = 100 Hz
- **Gun solenoid** located at 0.3 m from the cathode

SwissFEL photocathode (R. Ganter):

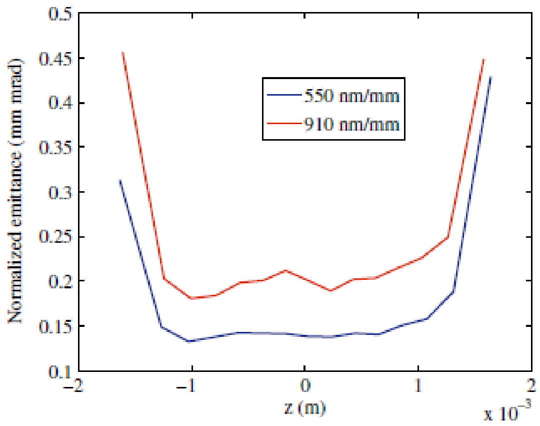
- Cs_2Te grown in house
- Measured QE~1%
- Lifetime of few years: stable QE after an initial degradation (3 cathodes exchanged from 2016 till now)
- Measured **intrinsic emittance**~550 nm/mm



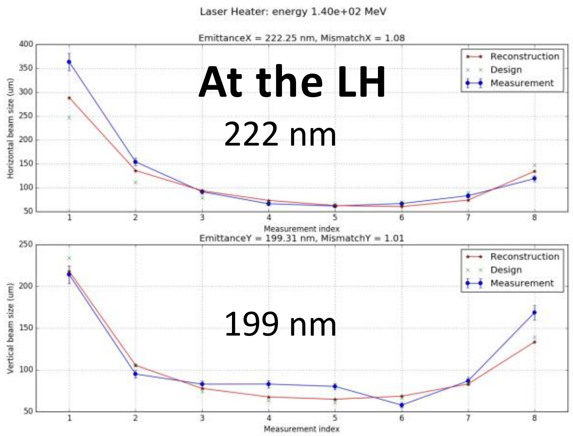
Where we are at SwissFEL (injector)

- SwissFEL design foresees a very small emittance for FEL photo-injectors
- The measurements reproduce what expected from the design at the highest charge (200 pC)
- Optimization in the machine mainly for 200 pC

Simulations



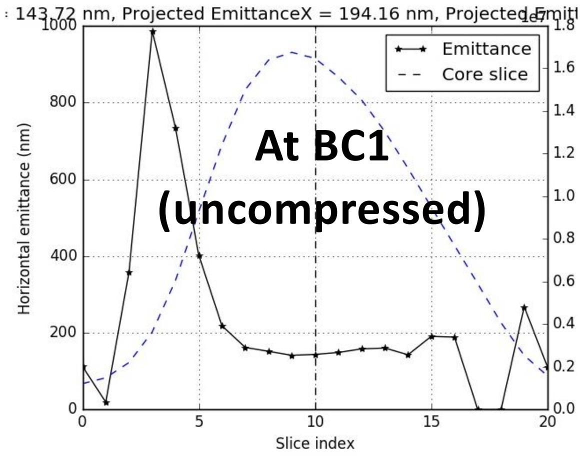
Measurements



At the LH

222 nm

199 nm



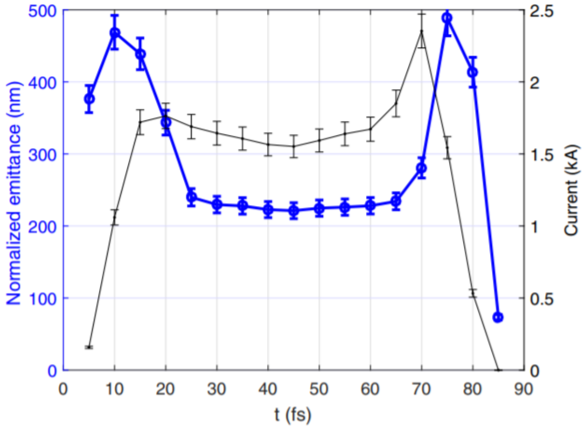
At BC1 (uncompressed)

Location	Measured (nm)	Design (nm)
LH (projected)	222 H-199 V	210
BC1 (slice)	140-150 H	145

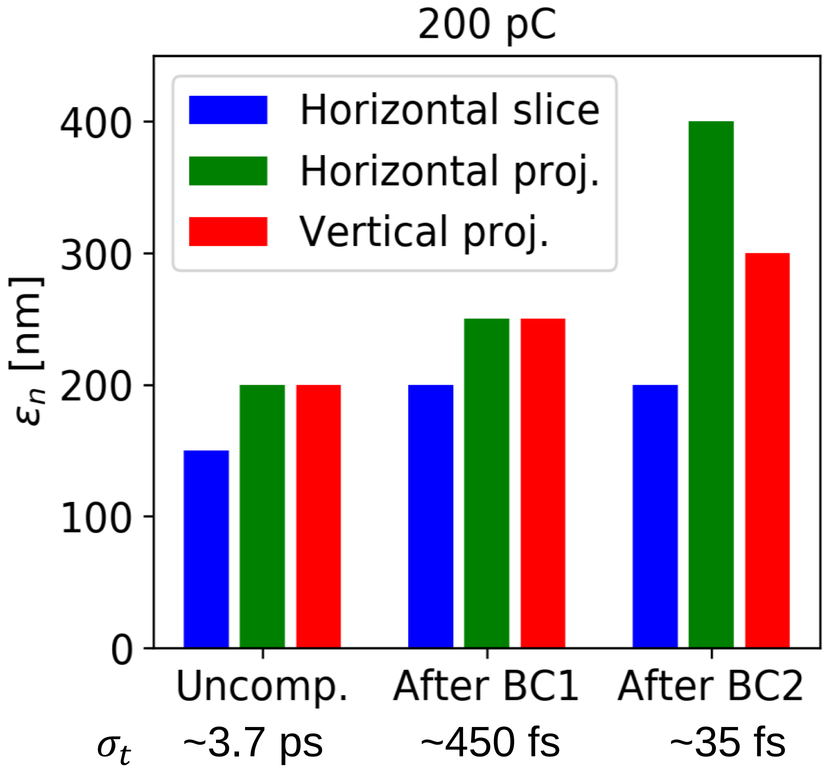
Simulations: https://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.18.123403

Measurements: https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.123.234801

Where we are at SwissFEL (undulator line(s))



Pulse duration (rms)	Slice (nm) H
44 fs (startup)	~330
35 fs (startup)	~300
35 fs (after optimization)	~200
25 fs (after optimization)	~320



- Start-to-end simulations (Astra-Elegant-CSRTrack-Elegant-CSRTrack-Elegant) foresee less than 20% slice emittance increase from the injector to the Aramis entrance for 3 kA
- Short-term reproducibility of measured emittance is about 2%, and longer-term reproducibility is about 20%. With a careful optimization smaller values recovered.

https://conf.slac.stanford.edu/photocathode-physics-photoinjectors-2021/sites/ppp2021.conf.slac.stanford.edu/files/SessionC_Ganter_Presentation.pdf
https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.123.234801

Different contributions to the emittance

The (small) final emittance is due to several contributions:

- Thermal/intrinsic $\varepsilon_{\text{int}} = \sigma_l \sqrt{\frac{2E_K}{3m_e c^2}},$ Cathode properties, and energy excess (low)
- Space charge $\varepsilon^{sc}_{n,i} = \frac{AQ}{8\sqrt{2\pi}\varepsilon_o c\sigma_i E_o \sin\phi_o}\mu_i(A);$ i=x or y. Energy gain of the beam (high)
- Rf emittance $\varepsilon^{rf}_{n,i} = \frac{eE_o}{2\sqrt{2}m_o c^2}k^2\sigma_i^2\sigma_z^2$ Gun frequency (low) and peak field (low)

The dominating contributions are typically the space charge and the intrinsic emittance

⬇

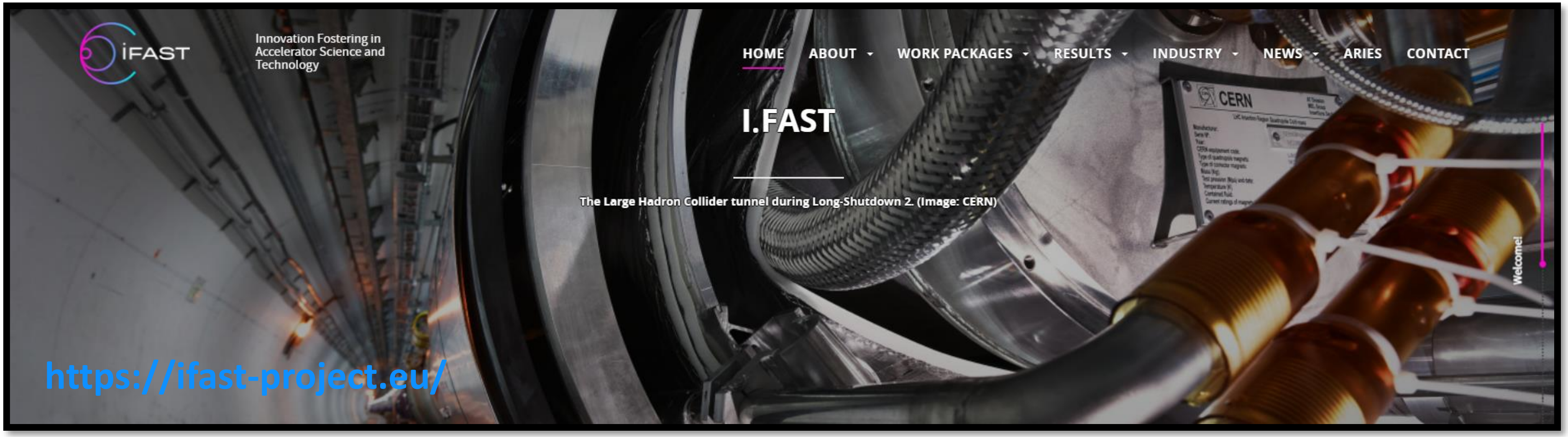
In the present SwissFEL case the **intrinsic emittance** contributes at **68%** to the final emittance of the uncompressed beam

https://linac96.web.cern.ch/proceedings/Tuesday/TU204/Paper.html

IFAST collaboration

Innovation Fostering in Accelerator Science and Technology

- **Goal**: investigate future accelerator technologies, particularly ones which are related to the size and performance of the machines
- **Task force**: 49 partners, including 17 companies, all from 14 countries
- **Budget**: 18.7 Meuro (120 kEuro+100 kEuro for PSI rf gun development and rf test)
- **Time frame**: from May 2021 to April 2025

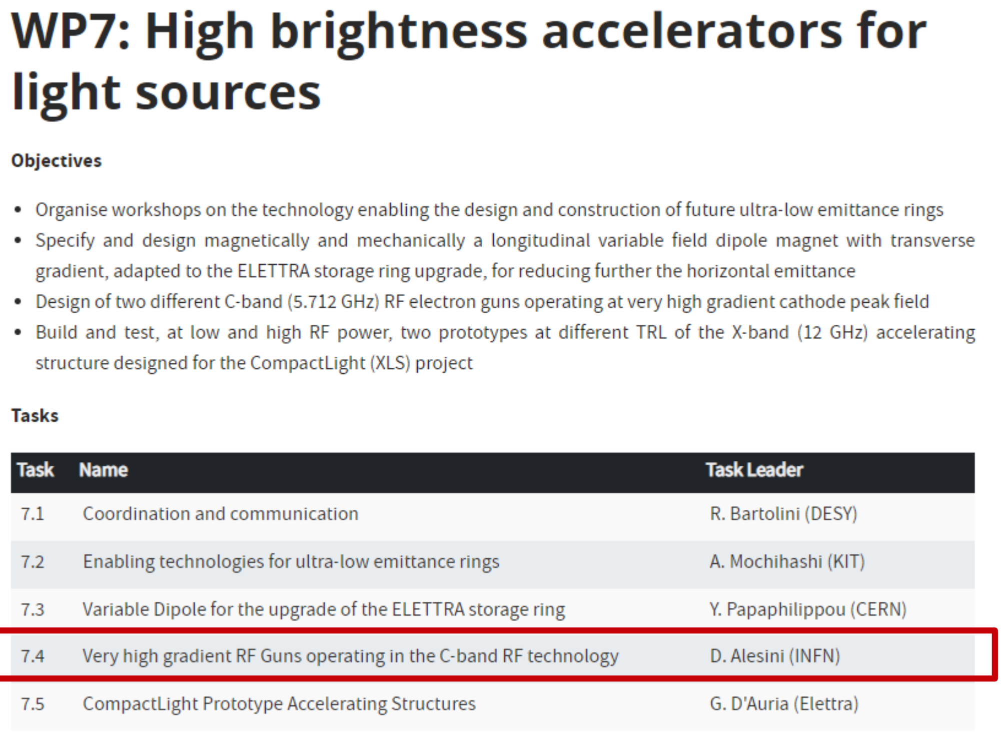


The Large Hadron Collider tunnel during Long-Shutdown 2. (Image: CERN)

https://ifast-project.eu/

PSI (rf section) is part of it

PSI-LNF



WP7: High brightness accelerators for light sources

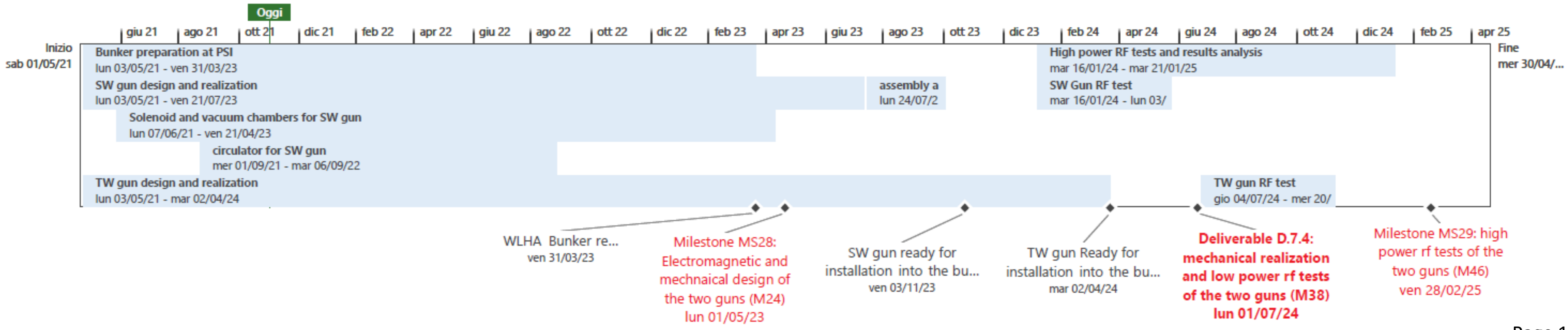
Objectives

- Organise workshops on the technology enabling the design and construction of future ultra-low emittance rings
- Specify and design magnetically and mechanically a longitudinal variable field dipole magnet with transverse gradient, adapted to the ELETTRA storage ring upgrade, for reducing further the horizontal emittance
- Design of two different C-band (5.712 GHz) RF electron guns operating at very high gradient cathode peak field
- Build and test, at low and high RF power, two prototypes at different TRL of the X-band (12 GHz) accelerating structure designed for the CompactLight (XLS) project

Tasks

Task	Name	Task Leader
7.1	Coordination and communication	R. Bartolini (DESY)
7.2	Enabling technologies for ultra-low emittance rings	A. Mochihashi (KIT)
7.3	Variable Dipole for the upgrade of the ELETTRA storage ring	Y. Papaphilippou (CERN)
7.4	Very high gradient RF Guns operating in the C-band RF technology	D. Alesini (INFN)
7.5	CompactLight Prototype Accelerating Structures	G. D'Auria (Elettra)

- Design, realization and high power test of two different **C-band** (5.712 GHz) rf electron guns operating at **peak field>160 MV/m**:
- A Standing Wave (**SW**) gun at Frascati and a Travelling Wave (**TW**) gun at PSI
- **Comparison** of the performances
- **Beam dynamics** simulations to exploit the device potentialities



Responsibilities

- **INFN**: coordination, **design** and low power test **SW Gun**, **solenoid** design and procurement, **design of the module** to test the gun, providing the **RF circulator**.
- **COMEB**: mechanical **construction SW gun**, mechanical **supports** and **movable screen with magnetic corrector**.

SW GUN

- **PSI: design, assembly, brazing** and low-power characterization of the **TW Gun**, hosting and setting up the **high-power test**.
- **VDL: Machining** of the cups and couplers of the **TW gun**.

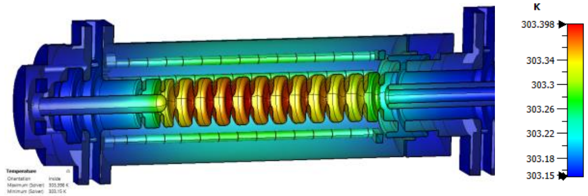
TW GUN

INFN and PSI: A comprehensive study and optimization of the **beam dynamics** aspects, to fully exploit the devices potentialities, will be led by

IFAST collaboration: PSI

Engineering by T. G. Lucas

Parameter	Value	Unit
Frequency	5712	MHz
Phase advance	120	deg
Repetion rate	100	Hz
Group velocity	0.0079	
Q	10000	
R/Q	8268	W/m
Regular cell	10	
RF length	220	mm
Filling time	90	ns



Gradient at cathode	135	MV/m
Gun output energy	12.7	MeV

Gradient at cathode	200	MV/m
Gun output energy	13.9	MeV

Present status:

- Beam dynamics optimizations (see next slide)
- Dark current simulations performed
- Heating of the gun at such high gradient computed
- Multipacting simulated
- Tolerance studies evidenced the need for a different input coupler design (presently ongoing)

T. G. Lucas GFA seminar Nov 2021, M. Schär PhD thesis, rf section

IFAST collaboration: PSI: BD expectations

Optimized configurations:

gun solenoid close to the cathode, beam energy increased soon (space charge)

- Lower (135 MV/m) AND higher (200 MV/m) gradient
- Minimum emittance AND similar emittance with more peak current

M. Schaer PhD thesis

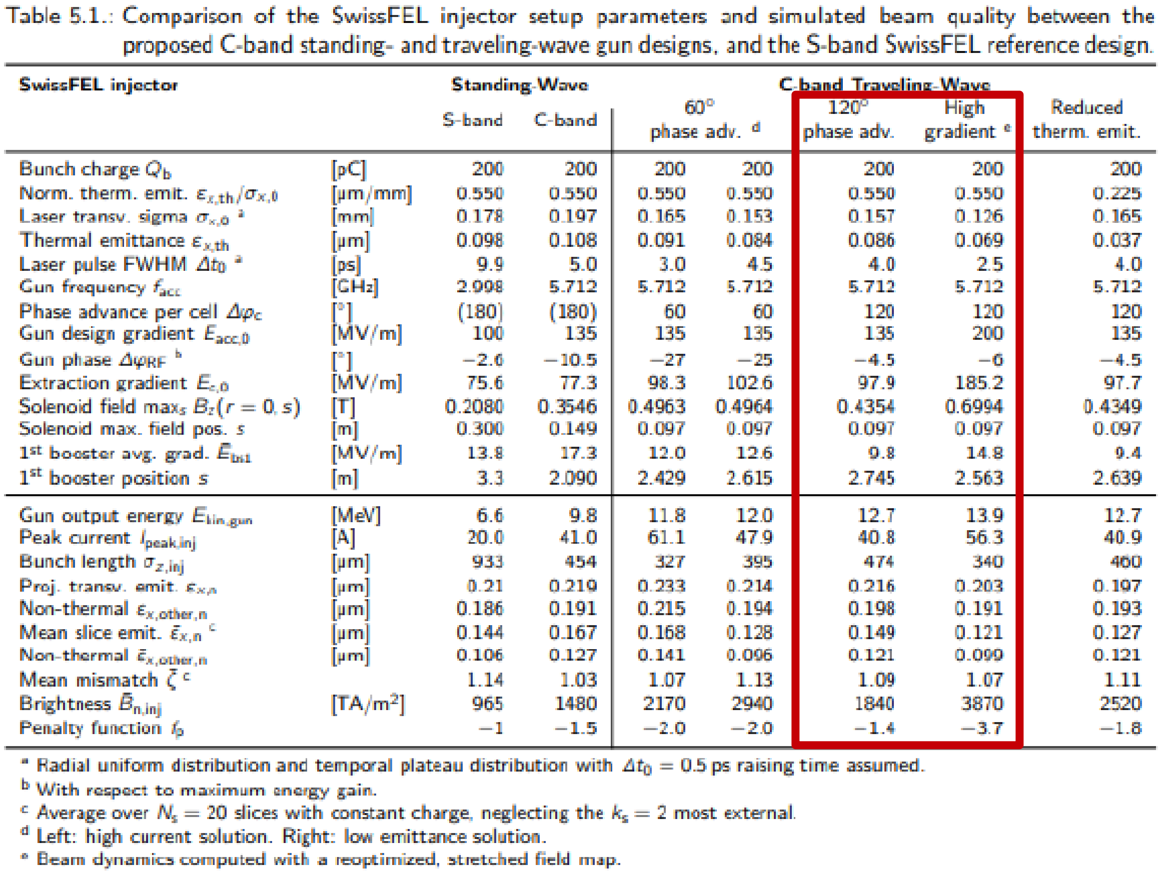


Table 5.1.: Comparison of the SwissFEL injector setup parameters and simulated beam quality between the proposed C-band standing- and traveling-wave gun designs, and the S-band SwissFEL reference design.

SwissFEL injector		**Standing-Wave**		**C-band Traveling-Wave**				
		S-band	C-band	60° phase adv. [d]		120° phase adv.	High gradient [e]	Reduced therm. emit.
Bunch charge Q_b	[pC]	200	200	200	200	200	200	200
Norm. therm. emit. $\varepsilon_{x,\mathrm{th}}/\sigma_{x,0}$	[µm/mm]	0.550	0.550	0.550	0.550	0.550	0.550	0.225
Laser transv. sigma $\sigma_{x,0}$ [a]	[mm]	0.178	0.197	0.165	0.153	0.157	0.126	0.165
Thermal emittance $\varepsilon_{x,\mathrm{th}}$	[µm]	0.098	0.108	0.091	0.084	0.086	0.069	0.037
Laser pulse FWHM Δt_0 [a]	[ps]	9.9	5.0	3.0	4.5	4.0	2.5	4.0
Gun frequency f_{acc}	[GHz]	2.998	5.712	5.712	5.712	5.712	5.712	5.712
Phase advance per cell $\Delta\varphi_c$	[°]	(180)	(180)	60	60	120	120	120
Gun design gradient $E_{\mathrm{acc},0}$	[MV/m]	100	135	135	135	135	200	135
Gun phase $\Delta\varphi_{\mathrm{RF}}$ [b]	[°]	−2.6	−10.5	−27	−25	−4.5	−6	−4.5
Extraction gradient $E_{z,0}$	[MV/m]	75.6	77.3	98.3	102.6	97.9	185.2	97.7
Solenoid field max$_s$ $B_z(r=0,s)$	[T]	0.2080	0.3546	0.4963	0.4964	0.4354	0.6994	0.4349
Solenoid max. field pos. s	[m]	0.300	0.149	0.097	0.097	0.097	0.097	0.097
1st booster avg. grad. $\bar{E}_{\mathrm{bs1}}$	[MV/m]	13.8	17.3	12.0	12.6	9.8	14.8	9.4
1st booster position s	[m]	3.3	2.090	2.429	2.615	2.745	2.563	2.639
Gun output energy $E_{\mathrm{kin,gun}}$	[MeV]	6.6	9.8	11.8	12.0	12.7	13.9	12.7
Peak current $I_{\mathrm{peak,inj}}$	[A]	20.0	41.0	61.1	47.9	40.8	56.3	40.9
Bunch length $\sigma_{z,\mathrm{inj}}$	[µm]	933	454	327	395	474	340	460
Proj. transv. emit. $\varepsilon_{x,n}$	[µm]	0.21	0.219	0.233	0.214	0.216	0.203	0.197
Non-thermal $\varepsilon_{x,\mathrm{other},n}$	[µm]	0.186	0.191	0.215	0.194	0.198	0.191	0.193
Mean slice emit. $\bar{\varepsilon}_{x,n}$ [c]	[µm]	0.144	0.167	0.168	0.128	0.149	0.121	0.127
Non-thermal $\bar{\varepsilon}_{x,\mathrm{other},n}$	[µm]	0.106	0.127	0.141	0.096	0.121	0.099	0.121
Mean mismatch $\bar{\zeta}$ [c]		1.14	1.03	1.07	1.13	1.09	1.07	1.11
Brightness $\bar{B}_{n,\mathrm{inj}}$	[TA/m^2]	965	1480	2170	2940	1840	3870	2520
Penalty function f_p		−1	−1.5	−2.0	−2.0	−1.4	−3.7	−1.8

[a] Radial uniform distribution and temporal plateau distribution with $\Delta t_0 = 0.5$ ps raising time assumed.
[b] With respect to maximum energy gain.
[c] Average over $N_s = 20$ slices with constant charge, neglecting the $k_s = 2$ most external.
[d] Left: high current solution. Right: low emittance solution.
[e] Beam dynamics computed with a reoptimized, stretched field map.

Up to a **factor 4** brightness (I/(eps_x*eps_y)) expected from simulations

Thermal emittance contributes to **71%** (135 MV/m) and **74%** (200 MV/m) to the final emittance

To be confirmed at the high field at the cathode (see later)

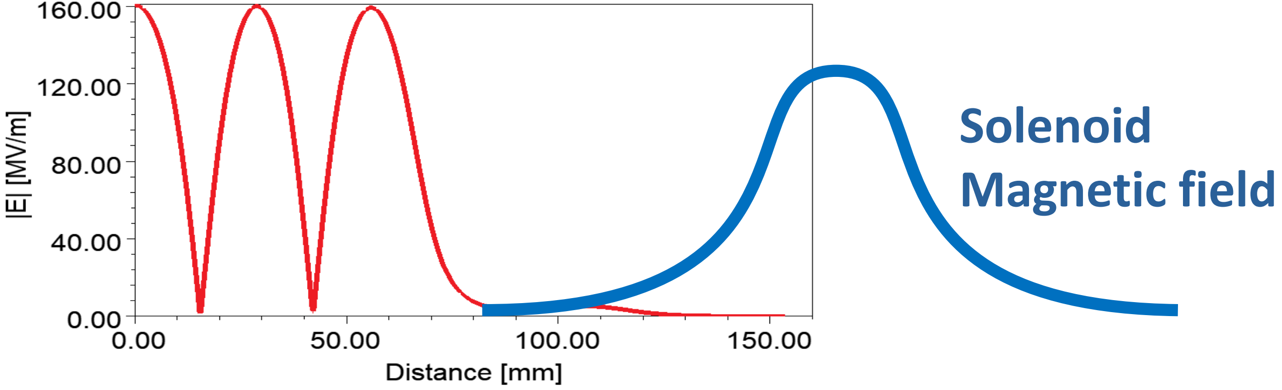
https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.19.072001

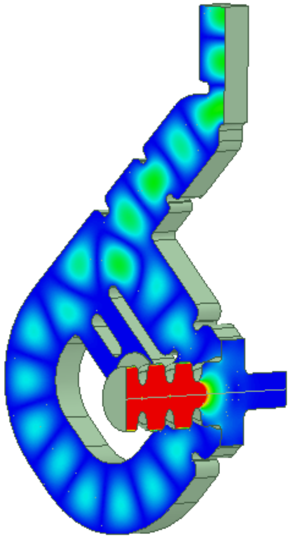
IFAST collaboration: INFN Frascati

Present status:

- 2.6 cells
- Electromagnetic design completed
- Gun solenoid and bucking coil design ongoing
- Dark current simulations performed

	Value	
Frequency [GHz]	5.712	
$E_{cath}/\sqrt{P_{diss}}$ [MV/(m·MW$^{0.5}$)]	51.4	
Peak input power [MW]	18	23
Cathode field [MV/m]	160	180
Cathode type	copper	
Rep. rate [Hz]	1000	100
Quality factor	11900	
Filling time [ns]	166	
Coupling coefficient	3	
RF pulse length [ns]	300	
E_{surf}/E_{cath}	0.96	
Mod. Poy. Vect. [W/μm^2]	2.5	3.1
Pulsed heating [°C]	16	20
Av.diss. Power [W]	2300	300


Longitudinal electric field profile



David Alesini and P. Craievich (private communication)

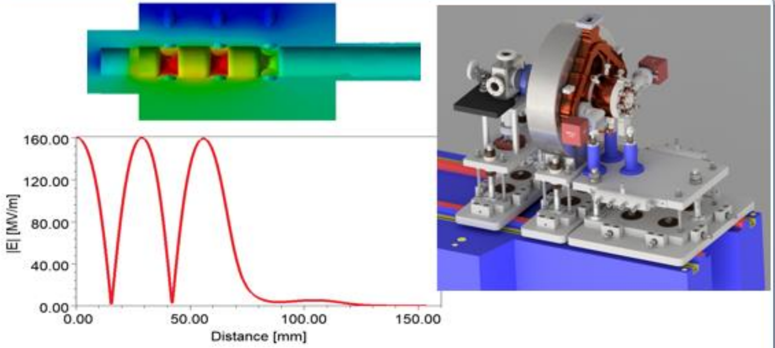
IFAST collaboration: INFN Frascati

Courtesy of A. Giribono (INFN-Frascati)

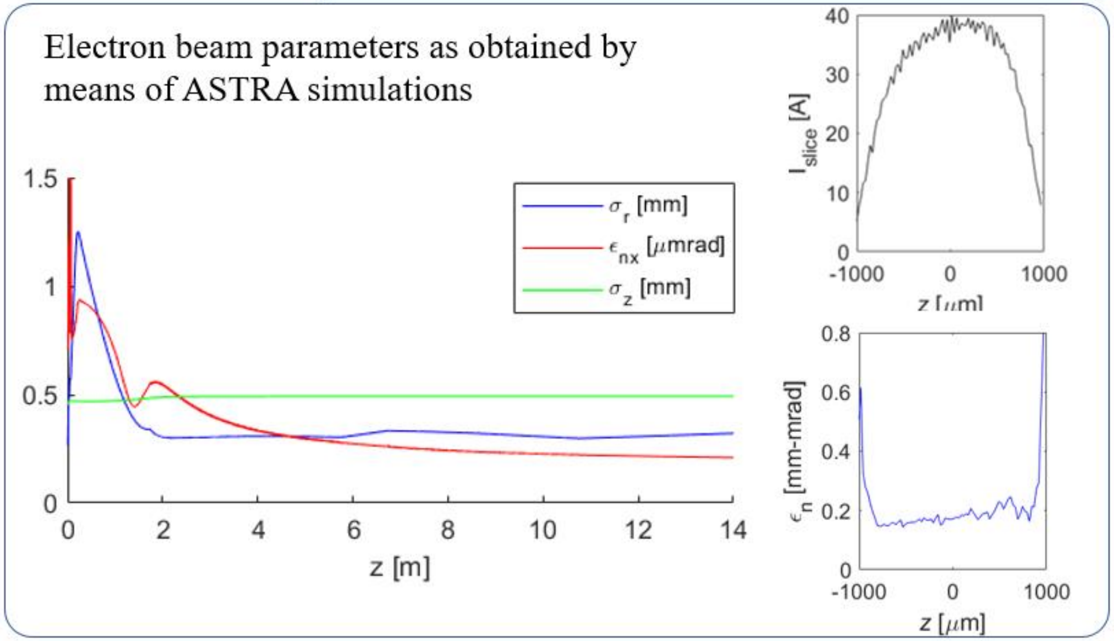
Preliminary optimization at our parameters range: analytical solution and optimizer

- The C-band RF gun has been designed and simulated at LNF. It consists of a 2.6 cells and a single coil solenoid for the emittance compensation

Parameters		Units
Q	200	pC
RF gun peak field	180	MV/m
Solenoid field max position	0.191	m
First S-band structure position	1.7	m
Intrinsic emittance	0.550	μm/mm
E	120	MeV
σ_E/E	0.05	%
$\epsilon_{n,rms}$	0.21	μm
Mismatch	1.06	
σ_z	475	μm
I_{peak}	40	A



RF gun electro-magnetic design



Electron beam parameters as obtained by means of ASTRA simulations

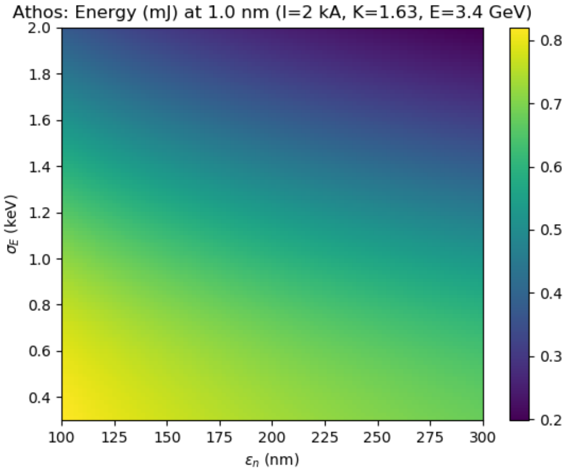
Impact on Porthos and the other lines

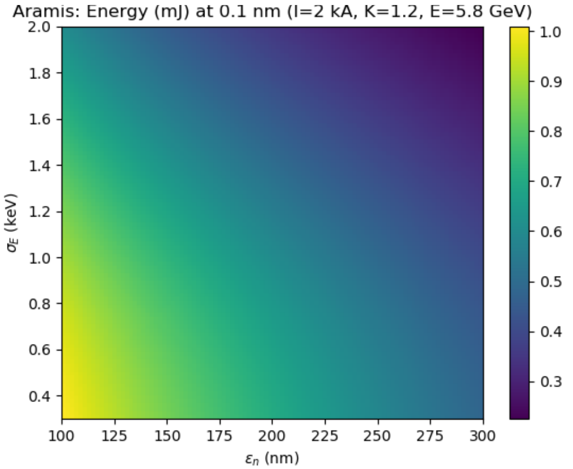
The condition:

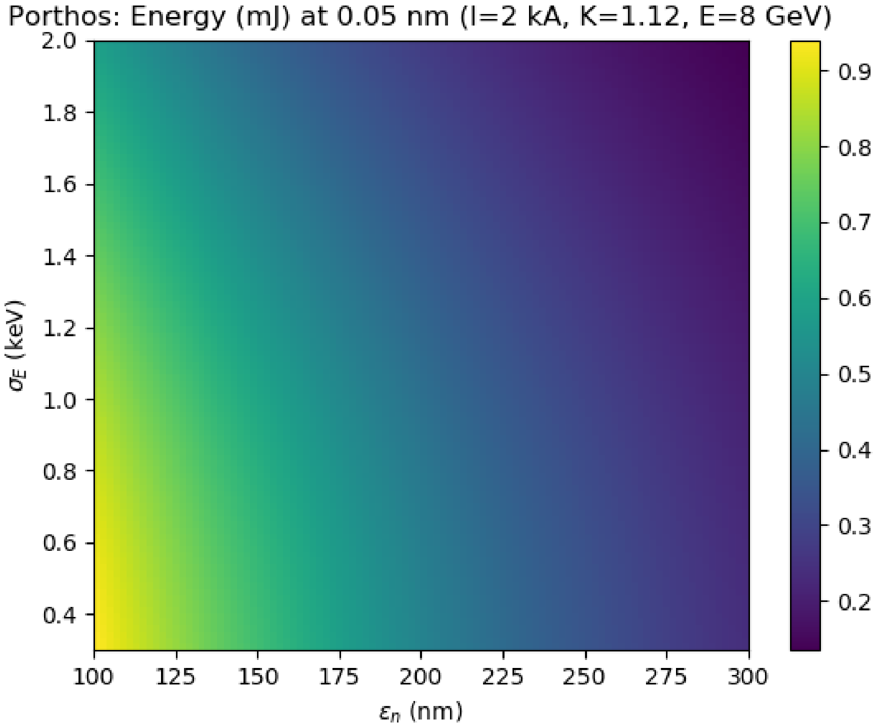
$$\boxed{\frac{\varepsilon_n}{\gamma} \leq \frac{\lambda}{4\pi}}$$

Courtesy of S. Reiche

is well fulfilled at lower energy, then not much benefits expected even further reducing the emittance.


Athos: Energy (mJ) at 1.0 nm (I=2 kA, K=1.63, E=3.4 GeV)


Aramis: Energy (mJ) at 0.1 nm (I=2 kA, K=1.2, E=5.8 GeV)

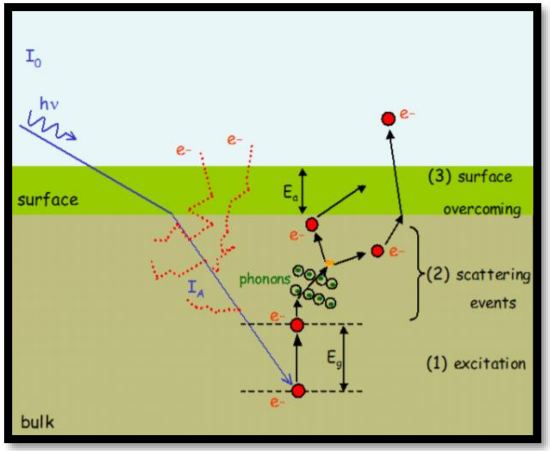

Porthos: Energy (mJ) at 0.05 nm (I=2 kA, K=1.12, E=8 GeV)

The impact on the emittance is more pronounced at high photon energies.

Emittance at the cathodes: remind

Three step model:

1. **Excitation**: electrons are excited from the valence band to the conduction band
2. **Transport**: electrons move within the photocathode
3. **Emission**: electrons with sufficient momentum perpendicular to the surface tunnel out into vacuum



Emittance at the cathode (intrinsic/thermal):

$$\varepsilon_{\text{int}} = \sigma_l \sqrt{\frac{2E_K}{3m_e c^2}}, \quad \Longleftrightarrow \quad \varepsilon = \sigma_x \sqrt{\frac{\text{MTE}}{m_e c^2}}$$

MTE: mean transverse energy

E_K: kinetic energy

E_K is defined as:

$$\text{metals}: \; 2E_K = \phi_l - \phi_w + \phi_{\text{Sch}},$$

$$\text{semiconductors}: \; 2E_K = \phi_l - E_g - E_a + \phi_{\text{Sch}},$$

ϕ_l: laser energy hν E_g: energy gap E_a: electron affinity

The term takes in account the field at the extraction time and the roughness surface of the cathode:

$$\phi_{\text{Sch}} = \sqrt{\frac{e^3}{4\pi\varepsilon_0}\beta E_c},$$

This term varies the potential wall height that the electrons must overcome to be emitted vs the field at the cathode at the extraction (E_c) and the surface roughness (β)

Formulas from: https://journals.aps.org/prab/pdf/10.1103/PhysRevSTAB.18.043401

Cathodes intrinsic emittance investigations at PSI

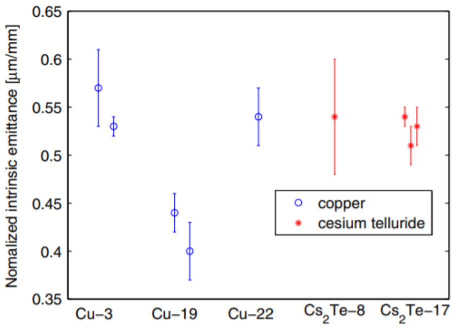
$$\varepsilon_{\text{int}} = \sigma_l \sqrt{\frac{2E_K}{3m_e c^2}},$$

$$\text{metals:}\ 2E_K = \phi_l - \phi_w + \phi_{\text{Sch}},$$

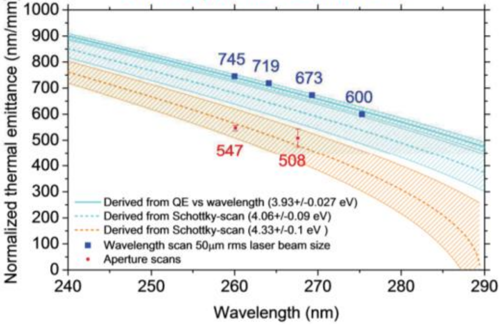
$$\text{semiconductors:}\ 2E_K = \phi_l - E_g - E_a + \phi_{\text{Sch}},$$

We performed a measurement campaign at PSI on the Cu and Cs_2Te intrinsic emittance (parameters used in the design)

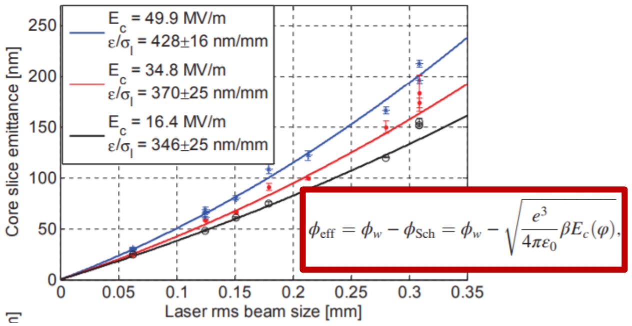
Material



Laser wavelength (Cu)



Field at the cathode(mainly Cu)



$$\phi_{\text{eff}} = \phi_w - \phi_{\text{Sch}} = \phi_w - \sqrt{\frac{e^3}{4\pi\varepsilon_0}\beta E_c(\varphi)},$$

For Cs_2Te we measured at 300 K, laser wavelength 262 nm about 550 nm/mm, which corresponds to MTE of about **155 meV**, and QE of the order of 1 or few **%**

Interplay between the intrinsic emittance and the quantum efficiency (QE)

Higher is the excess of energy with respect to Φ provided by the laser compared to the energy necessary to extract the electrons, higher are the QE and the intrinsic emittance.

Both must be measured to characterize the quality of the performances of a cathode.

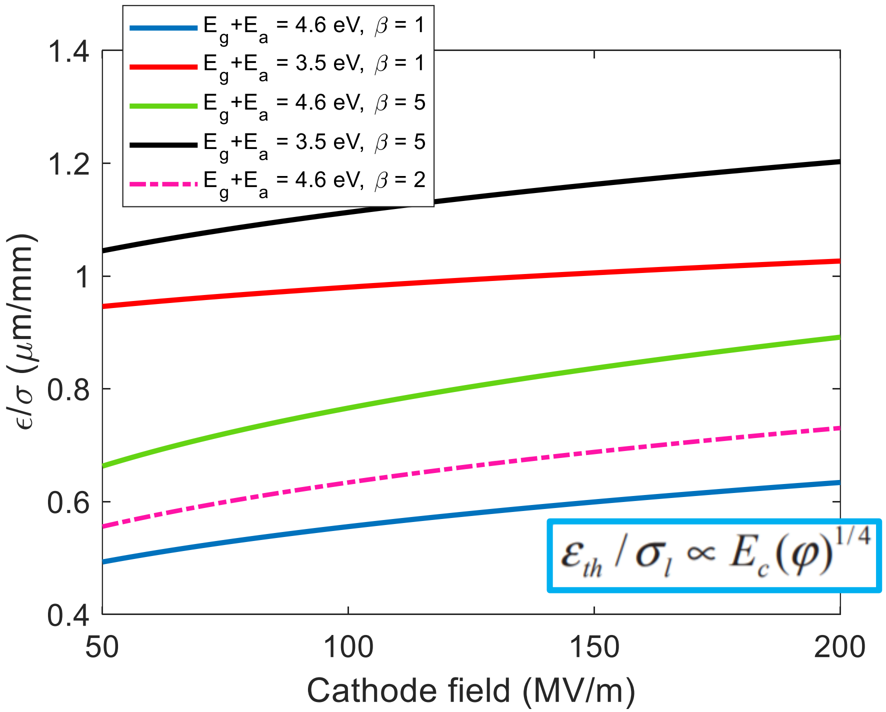
One article for each parameter scan, summary in: http://accelconf.web.cern.ch/FEL2014/talks/thc02_talk.pdf

Intrinsic emittance and cathode field E_C for Cs_2Te

$$\varepsilon_{\text{int}} = \sigma_l\sqrt{\frac{2E_K}{3m_ec^2}},$$

$$\text{semiconductors: } 2E_K = \phi_l - E_g - E_a + \phi_{\text{Sch}},$$

$$\boxed{\phi_{\text{Sch}} = \sqrt{\frac{e^3}{4\pi\varepsilon_0}\boxed{\beta}\boxed{E_c},}}$$



Possible improvements: increase the Schottky term:

- The local field enhancement factor β is very sensitive to cathode surface roughness → co-evaporation of the cathode seems to be beneficial
- Lower the field at the cathode at the time of the extraction is, lower the intrinsic emittance is

Formulas from: https://journals.aps.org/prab/pdf/10.1103/PhysRevSTAB.18.043401

Intrinsic emittance and cathode field E_C

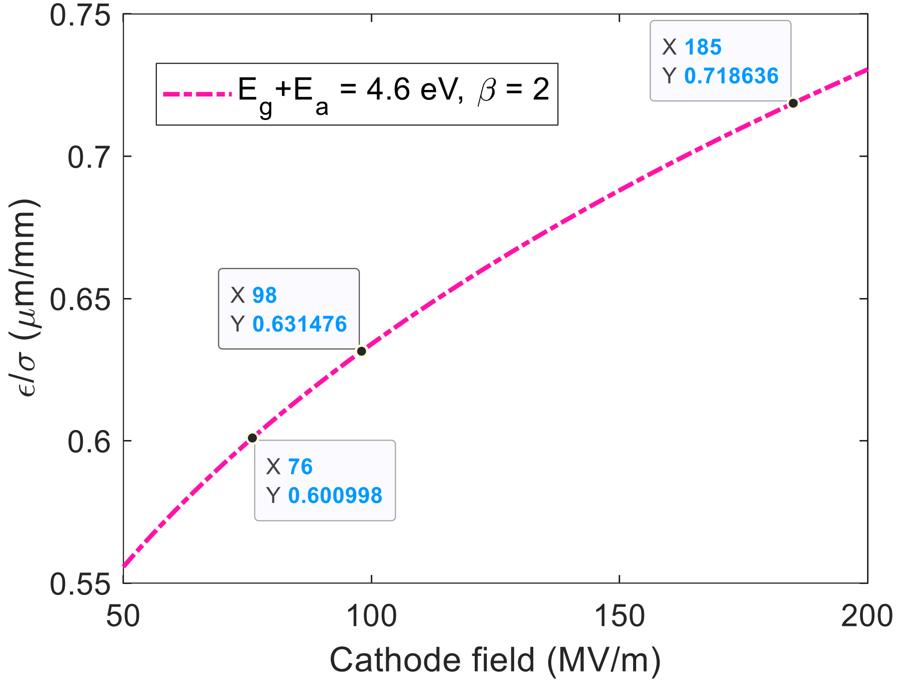
Present S-band SwissFEL gun

- On-axis peak field: 100 MV/m
- Field at the extraction: 76 MV/m

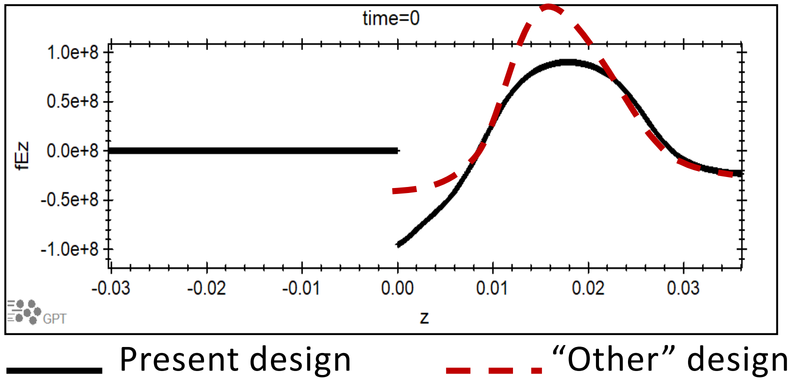
Future possible TW C-band PSI gun (similarly for the INFN case)

- On-axis peak field: 135 (200) MV/m
- Field at the extraction: 98 (185) MV/m

About 25% increase of the intrinsic emittance contribution in the worst case → about **20%** increase of the final emittance. Something to be verified.



- Is there an **optimal field** at the extraction?
  - **Lower** is beneficial → reduce the intrinsic emittance
  - **Higher** is beneficial → minimize the space charge effect soon
- Possible solutions → deform cathode, unbalance the field of the different cells, …
- Measurements to be done to estimate the field contribution on Cs_2Te cathode?



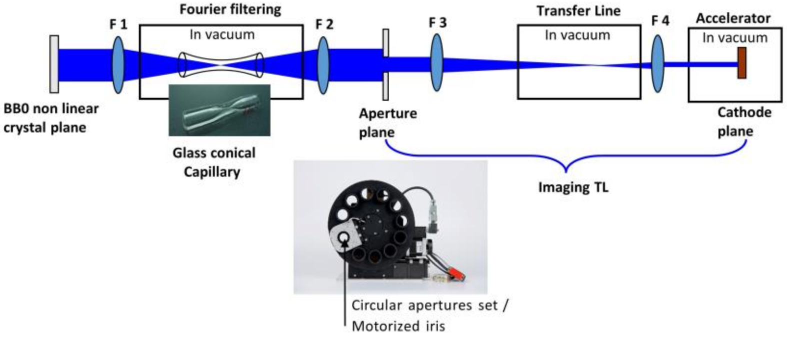
Field plot from L. T. Geoffrey

From Cu to Cs_2Te at SwissFEL

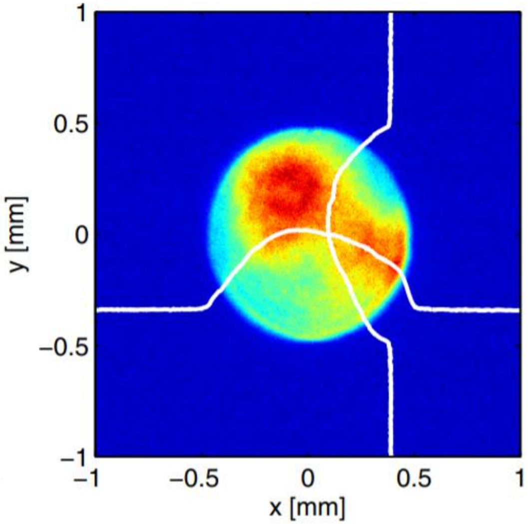
- The quality of the laser transverse profile σ_e is a fundamental parameter to optimize the emittance:

$$\sigma_e = \sigma_L x QE \quad \begin{cases} \sigma_L\text{: laser profile} \\ \text{QE: quantum efficiency map where the cathode is illuminated} \\ x \text{ convolution} \end{cases}$$

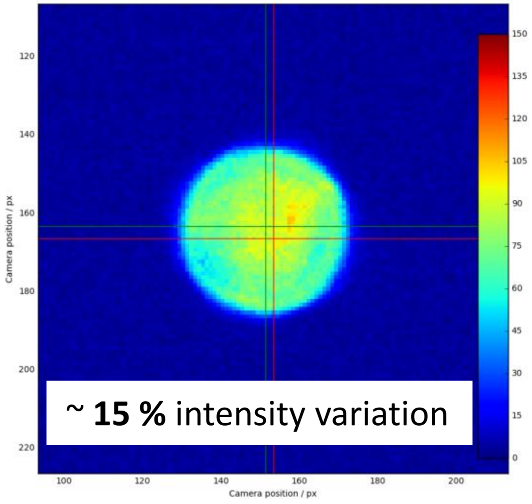
- A transverse shaping (TS) technique (energy hungry) may be used to improve the laser transverse profile uniformity



Cu cathode (W/O TS)



Cs_2Te cathode (W TS)



~ **15 %** intensity variation

Present situation with Cs_2Te:

- QE orders of magnitude larger for Cs_2Te vs for Cu
- Similar values for the intrinsic emittance
- More laser energy allows to apply transverse shaping

https://conf.slac.stanford.edu/photocathode-physics-photoinjectors-2021/sites/ppp2021.conf.slac.stanford.edu/files/SessionC_Ganter_Presentation.pdf

Other cathode materials

Main investigator: Cornell University, DESY PITZ

Many studies are going on at several labs on cathodes "efficiently" emitting in green, blue, or even red/IR (in this case at the present very low QE<1e-4)

- Reduction of the complexity, **cost** of the laser
- More laser intensity available at the cathode (reduced number of harmonics conversions) → better laser shaping → better **emittance**
- Reduction of the damaging of the **optics components**
- Some considered materials (mainly semiconductors) are **Cs_3Sb**, Rb-K-Sb, CsK_2Sb, **GaAs**

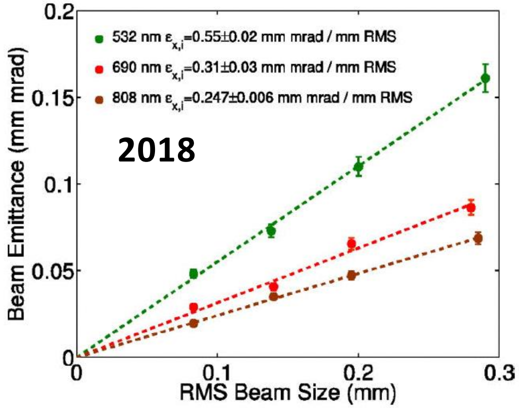
NOTE:

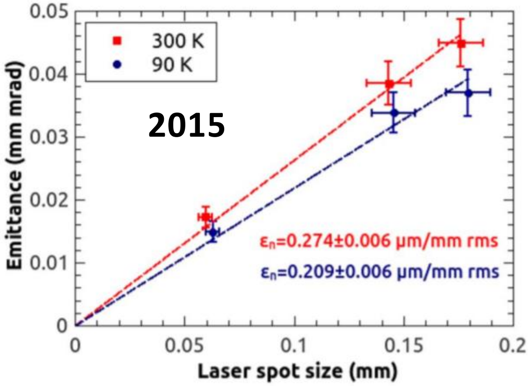
Many of the measurements are performed at a very low gradient, so also the excess of energy due to the effect of the electric field on the cathode must be considered.

Cs_3Sb photocathodes

Cornell University

Intrinsic emittance



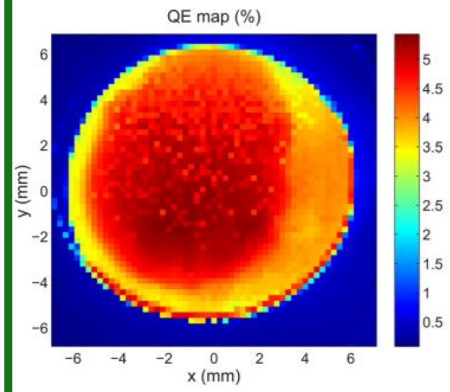


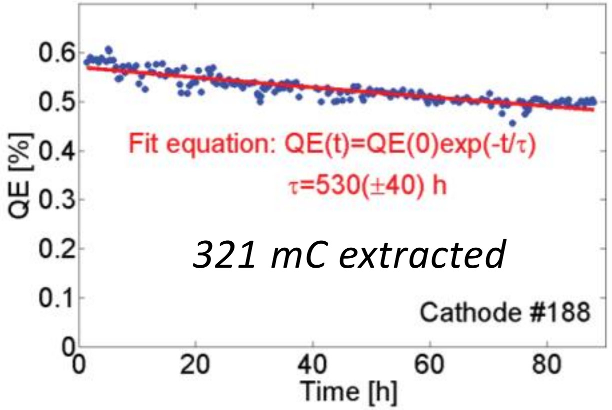
Laser λ (nm)	ε/σ (nm.rad)
532	550
690	310
808	247
690 (2015)	274

Similar values of Cs_2Te in UV but in green

Quantum efficiency

At 532 nm a fresh cathode starts from 5-10% QE, which degrades quickly to of the order of few per mille, where it seems to stabilize (no long term measurements found, and not at high gradient)





321 mC extracted

As a reference at SwissFEL the charge extracted/day:

Q_D = 2 bunch*200 pC*100 Hz*60 s*60 m*24 h corresponds to about 3.5 mC

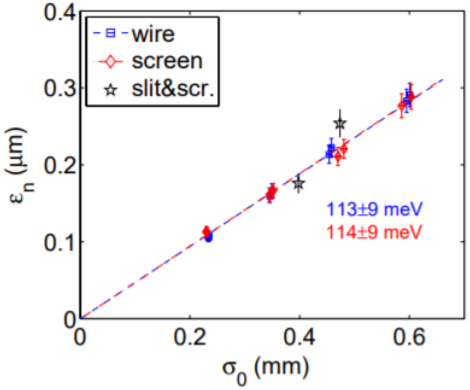
With also Porthos Q_D = 5.25 mC

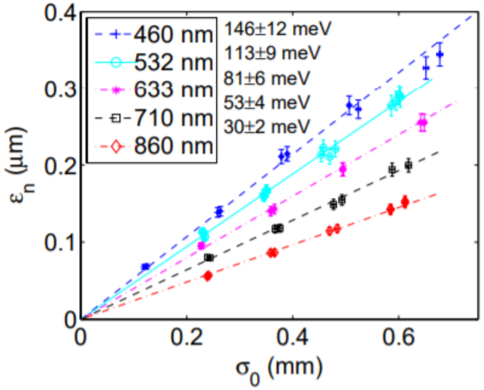
https://www.osti.gov/servlets/purl/1483870, https://aip.scitation.org/doi/pdf/10.1063/1.3652758

GaAs photocathodes

Cornell University

Intrinsic emittance

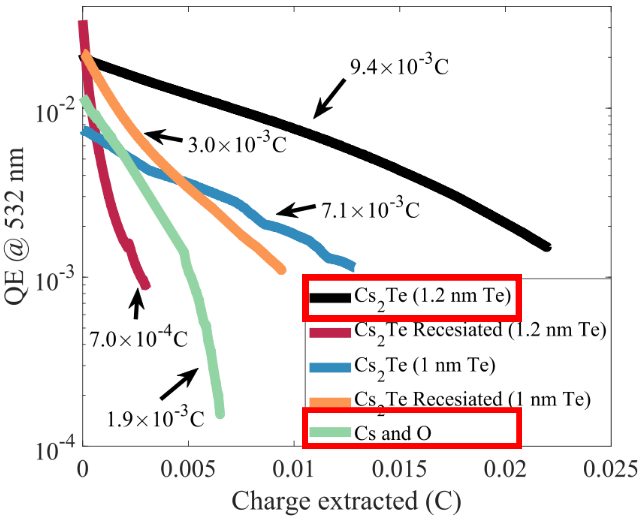




Cs_2Te has about 155 meV MTE

Better value of Cs_2Te (by 37%) in UV but in green

Quantum efficiency



- Layer of Cs_2Te to make the material more robust (increase the lifetime): increased by a factor 5 deposing Cs2Te on top of GaAs
- Measurements at higher gradient in preparation
- Not measurements of the intrinsic emittance done for this case

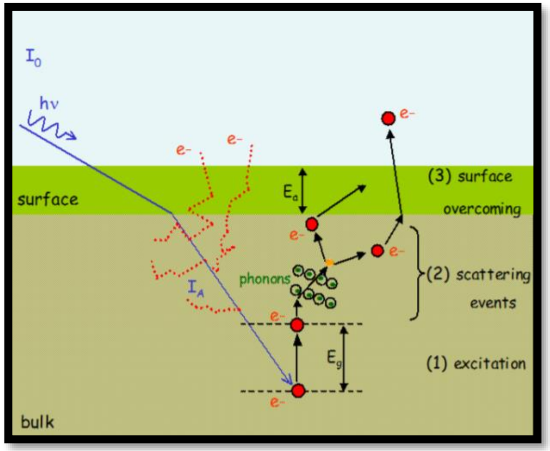
https://conf.slac.stanford.edu/photocathode-physics-photoinjectors-2021/sites/ppp2021.conf.slac.stanford.edu/files/SessionA_Biswas_Presentation.pptx
https://aip.scitation.org/doi/10.1063/5.0026839 https://accelconf.web.cern.ch/p07/PAPERS/TUPMS020.PDF

Cold cathodes

Cornell University

Three step model

1. **Excitation**: electrons are excited from the valence band to the conduction band
2. **Transport**: electrons move within the photocathode
3. **Emission**: electrons with sufficient momentum perpendicular to the surface tunnel out into vacuum

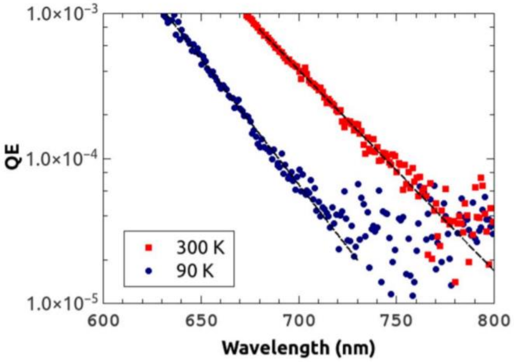


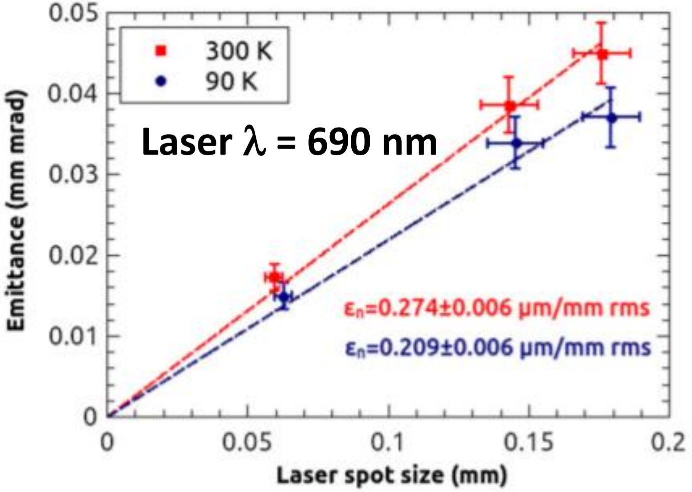
During 2 the electrons undergo to scattering with the material lattice

The equivalent temperature (i.e. intrinsic emittance) of the electron bunch increases

Cool down the cathode mitigates the intrinsic emittance increase

Experimental verification (Cs_3Sb)





Laser λ = 690 nm

About 25% intrinsic emittance reduction at 90 K vs at 300 K

No measurements done at higher accelerating fields (10’s to 100 MV/m)

https://journals.aps.org/prab/pdf/10.1103/PhysRevSTAB.18.113401

A speculation during the “brainstorming”

The beam emittance is given by the position spread, the angle or velocity spread and their combination:

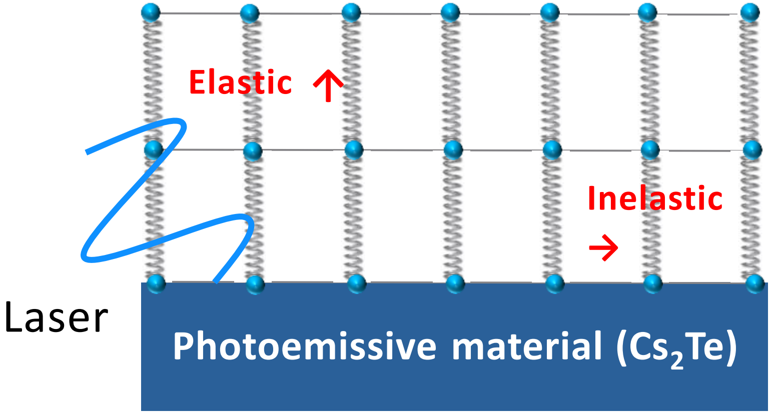
$$\boxed{\varepsilon_{\mathrm{RMS}} = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle x\cdot x'\rangle^2}}$$

x: position distribution of e-

x’: angle distribution of e-

A possibility to reduce the emittance is to intervene on the angle distribution

HOW TO REDUCE THE EMITTANCE AT THE EXTRACTION: PRINCIPLE



1. In the direction **normal** to the surface they undergo to **inelastic** scattering
2. In the direction **tangential** to the surface they undergo to **elastic** scattering

Use the journey to the extraction to “clean” the velocity spread and then reduce the emittance

FROM THE PRINCIPLE TO REALITY: THE UNIDIMENSIONAL CONDUCTORS?

Materials whose electrical conductivity is high only along one direction:

$$\boxed{\begin{array}{c} l_\parallel \gtrsim d_\parallel \\ l_\perp \ll d_\perp \end{array}}$$

$l_{\parallel\,(\perp)}$ is the electron mean free path

$d_{\parallel(\perp)}$ is the interatomic distance along the 1d axis

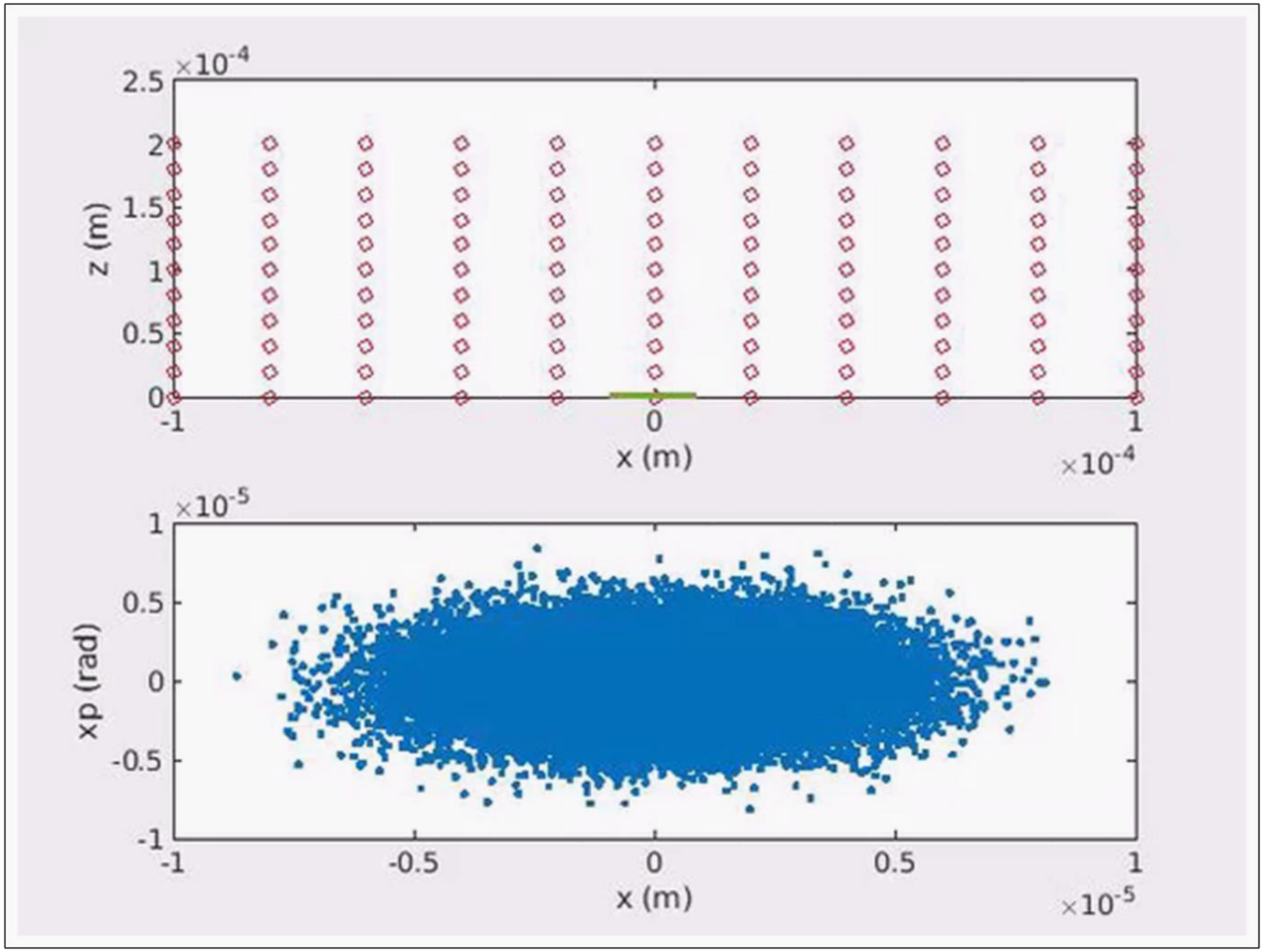
Platinum compounds, zirconium tritellurite

POSSIBLE COLLABORATION?

Informal and preliminary discussions with someone in EMPA, INFN Milan, INFN Frascati, ENEA to make this possibility something realistic and usable

Toy model in preparation

At each iteration with the lattice the e- velocity in x direction is reduced



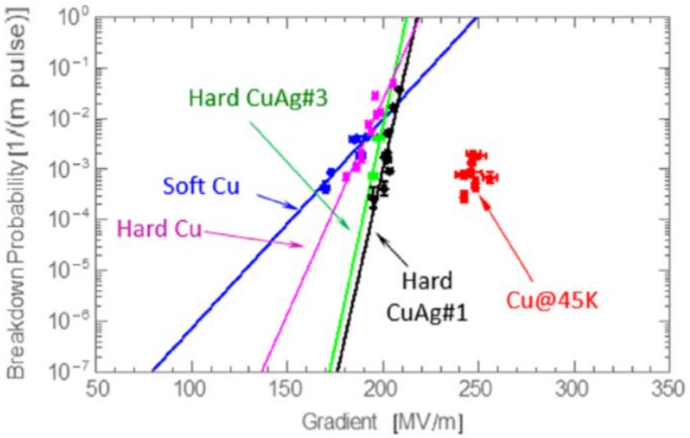
Determine the thickness as a function of the mean free path of the material

Cryo-cooled C-band rf guns

UCLA-SLAC-LNF

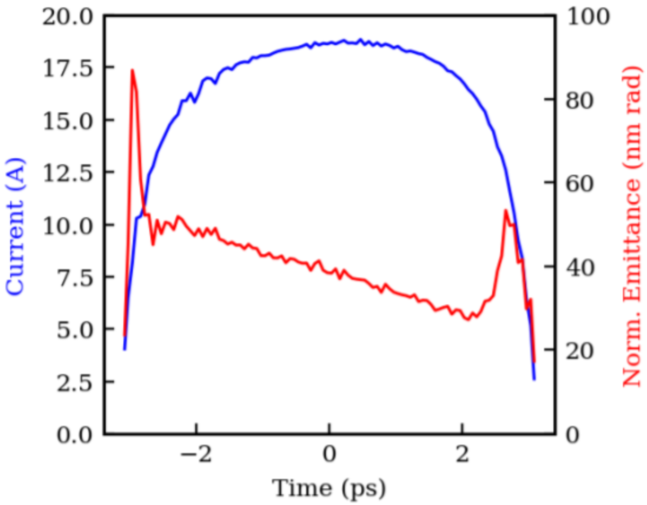
STATUS (Cu rf gun)

- At 45 K gradient of 500 MV/m experimentally achieved, but limitations due to dark current at 300 MV/m (cathode field)
- At 27 K peak design reaching 250 MV/m



EXPECTATIONS (250 MV/m case)

With the latter design 40 nm at 200 pC with 10 ps beam pulse length expected



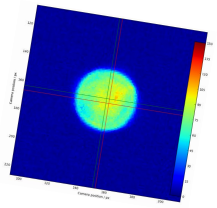
	Room temperature						Cryo-cooled
ε_N (um.rad)	0.144	0.167	0.168	0.128	0.149	0.121	**0.040**
Brightness	965	1480	2170	2940	1840	3870	**11875**

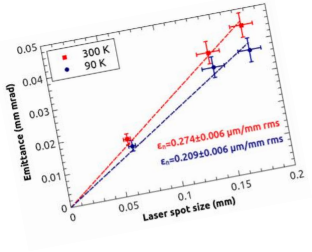
https://arxiv.org/ftp/arxiv/papers/1801/1801.06765.pdf and https://indico.fnal.gov/event/22025/contributions/210495/attachments/142307/179629/HG2021_AtsushiFukasawa.pdf

Intermediate summary on emittance optimization

GREEN (BLUE/RED) CATHODE: better for the laser (shaping, cost, optics lifetime)

- Intrinsic **emittance** using green laser **similar or better** than Cs_2Te using UV laser
- **Uniformity** of the **QE** of the order of few % (up to 5)
- **Roughness** of the cathode surface of the order of 1-2 nm rms
- Strong **vacuum activity** and even discharges in case the electric field at the cathode is increased to something of the order of more than few 10s MV/m (PITZ)
- QE degrades with vacuum
- No tests at gradient > 30-40 MV/m (not promising at these values already-PITZ)





POSSIBLE IMPROVEMENTS:

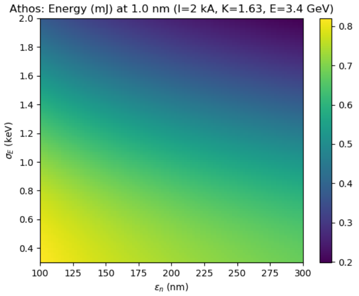
- **Cool down** the cathode: experimentally demonstrated at the expenses of the QE until now
- **Cryo-cooled** gun: up to 500 MV/m demonstrated, but 300 MV/m presently maintainable

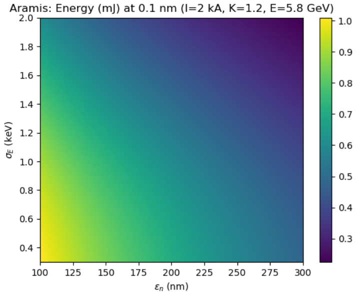
PROBABLY NOT MATURE ENOUGH YET TO BE INSTALLED IN A USER FACILITY

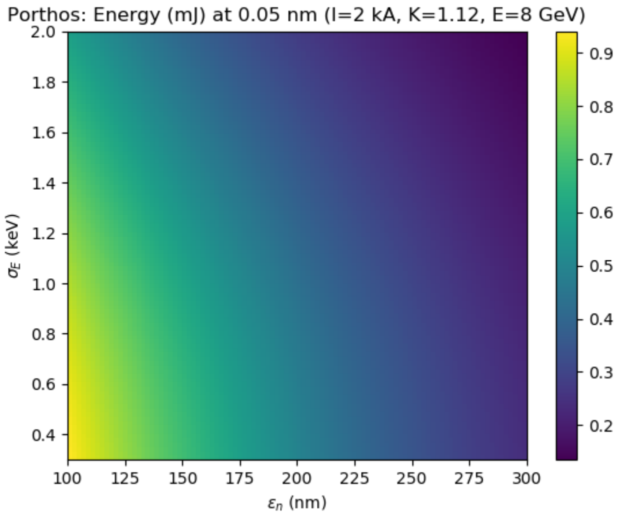
PROPOSALS:

- Tune the Cs_2Te **growing procedure** to stay more at the threshold to decrease the intrinsic emittance partially sacrificing QE
- More investigations on the **co-evaporation** of the cathode, and check the optimum for the cathode field at the extraction
- **"Cleaning" layer** or **orienting** of the Cs_2Te photocathode to reduce the intrinsic emittance?

Another character in the story: energy spread


Athos: Energy (mJ) at 1.0 nm (I=2 kA, K=1.63, E=3.4 GeV)


Aramis: Energy (mJ) at 0.1 nm (I=2 kA, K=1.2, E=5.8 GeV)


Porthos: Energy (mJ) at 0.05 nm (I=2 kA, K=1.12, E=8 GeV)

Small emittance

The FEL power and small wavelength (at given energy) rely on small emittance

Limited peak current at the injector

To minimize the emittance the initial peak current at the injector is limited (space charge)

Compress the beam

The saturation power increases with the peak current

Energy spread increases

The product of the bunch length and the energy spread is constant

The energy spread increases as the compression factor

Limit on the energy spread

The energy spread must be smaller than the parameter rho to efficiently lase

Emittance and energy spread (σ_γ)

Courtesy of S. Reiche

Intra-Beam Scattering

$$\frac{d}{dz}\sigma_\gamma^2 = \frac{2r_e^2 N_e}{\sigma_r \epsilon_n \sigma_z}$$

[Huang LCLS-TN-02-8]

Diffusion Process:

- Energy spread grows as $z^{1/2}$
- Energy spread scales as $\varepsilon_n^{-3/4}$

Microbunch Instability

$$\frac{d}{dz}\sigma_\gamma(k) = \frac{I}{I_A}\frac{2}{k\sigma_r^2}\left[1-\frac{k\sigma_r}{\gamma}K_1\left(\frac{k\sigma_r}{\gamma}\right)\right]b(k)$$

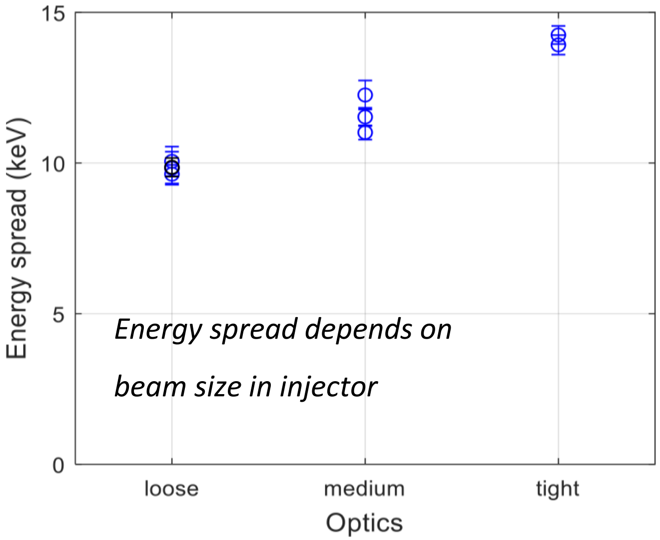
[Huang & Wu SLAC-PUB-11597]

Almost linear growth:

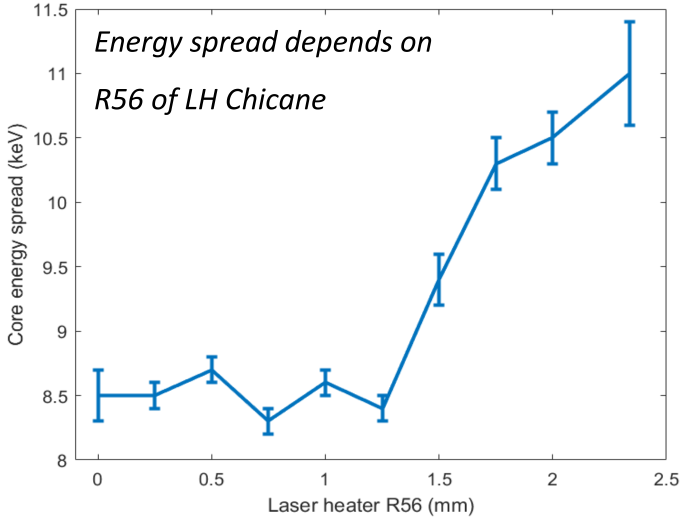
- 1D Limit for $k\sigma_r/\gamma \ll 1$ (σ_r drops out)
- LH chicane enhances certain high frequencies in the shot noise bunching spectrum, depending on beam emittance

Measurement of uncorrelated energy spread of uncompressed beam

[in preparation for publication]



Energy spread depends on beam size in injector



Energy spread depends on R56 of LH Chicane

First bunch compressor scales energy spread by compression factor and «freezes» it in

Emittance and FEL performance

Courtesy of S. Reiche

Coherence Condition

$$\boxed{\frac{\epsilon_n}{\gamma} < \frac{\lambda}{4\pi}}$$

Smaller emittances are needed to reach shorter wavelength

Energy Spread Condition

$$\boxed{C\frac{\sigma_\gamma}{\gamma} \leq \rho \propto \frac{1}{\gamma}\left[C\frac{I}{\epsilon_n}\right]^{\frac{1}{3}}}$$

With parameters at 1 Å (I = 2 kA and σ_E=12 keV) both sides are about equal (For compression scaling : C = 1)

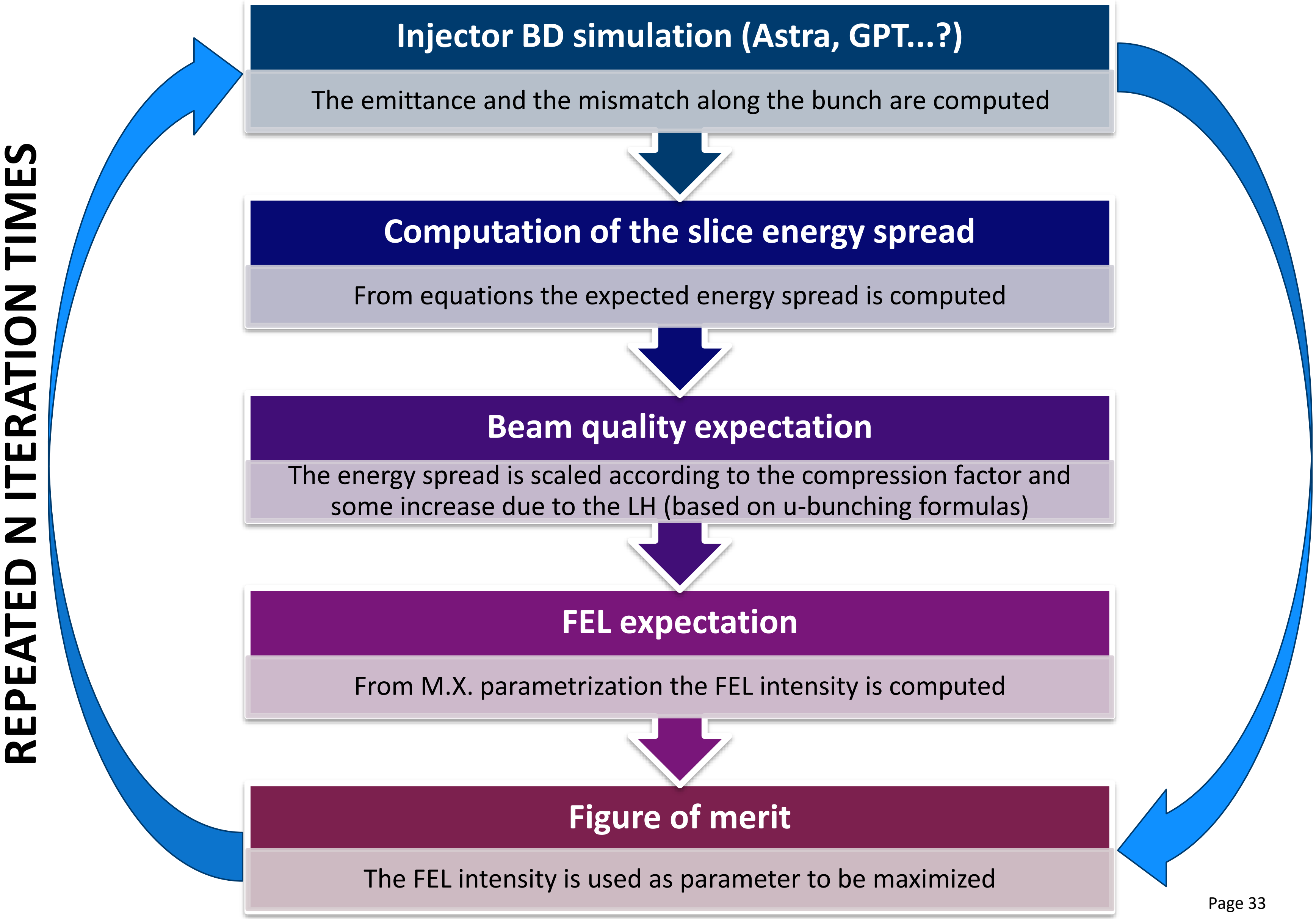
- Lower emittance at gun will increase energy spread stronger than FEL parameter ρ
- Bunch needs to be decompressed (C<1) to preserve energy spread condition

Benefit of smaller emittance is partially negated for SwissFEL if initial energy spread in the injector is not reduced

This counter action of the energy spread has an even stronger impact for wavelength shorter than 1 Angstrom

Proposal “best performance” optimization optimizer

Start-to-end simulations of the final gun to be installed in SwissFEL would be useful (see spare slide)



REPEATED N ITERATION TIMES

Injector BD simulation (Astra, GPT...?)

The emittance and the mismatch along the bunch are computed

Computation of the slice energy spread

From equations the expected energy spread is computed

Beam quality expectation

The energy spread is scaled according to the compression factor and some increase due to the LH (based on u-bunching formulas)

FEL expectation

From M.X. parametrization the FEL intensity is computed

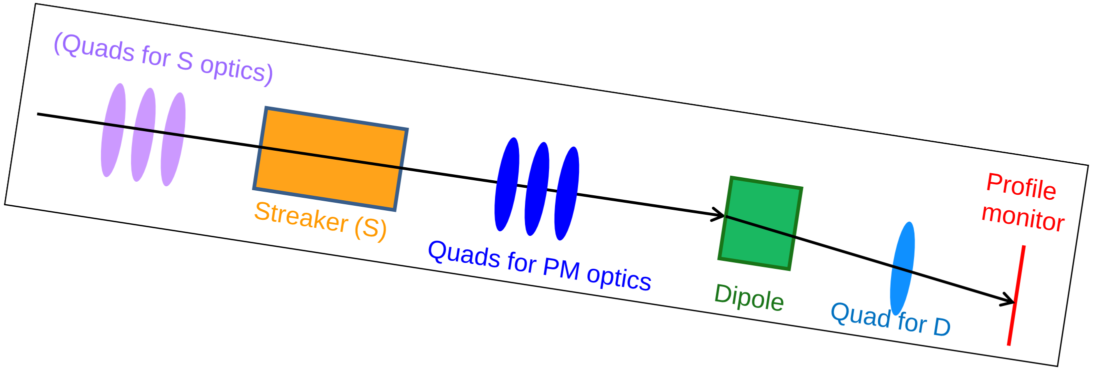
Figure of merit

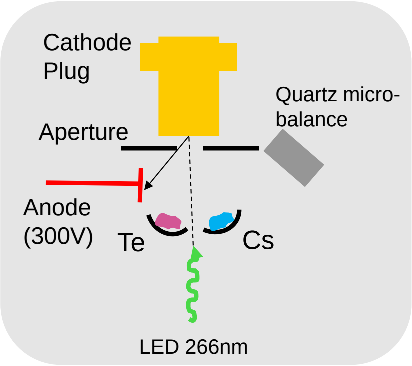
The FEL intensity is used as parameter to be maximized

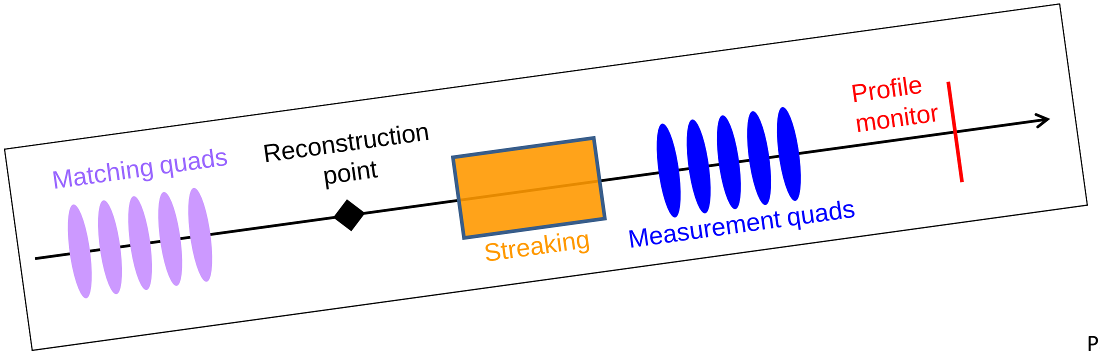
Crucial parameters to be measured

Several parameters must be verified before so invasively modify the SwissFEL injector:

- QE and QE map
- Energy spread (slice and projected?)
- Beam emittance (slice and projected?)
- Cathode lifetime (in case we will change cathode material), uniformity, and response time: not treated here





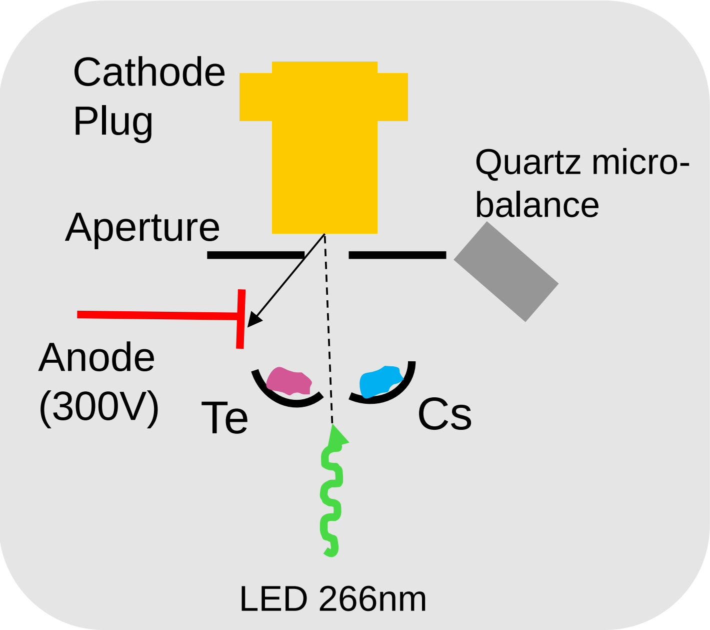


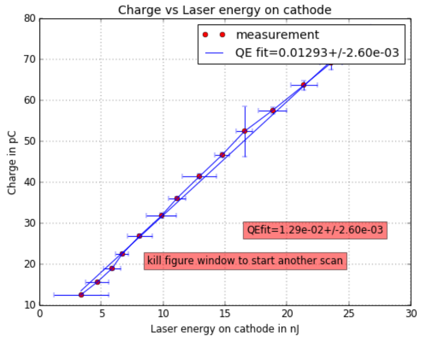
QE and QE map

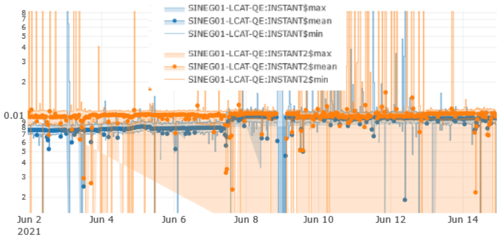
- Large quantum efficiency permits to have a better laser transverse shaping (beneficial for the emittance) and use less laser intensity (minimize the optics damages and reduce the operation cost)
- Semiconductors ~1% up to 10% (only for a limited time)

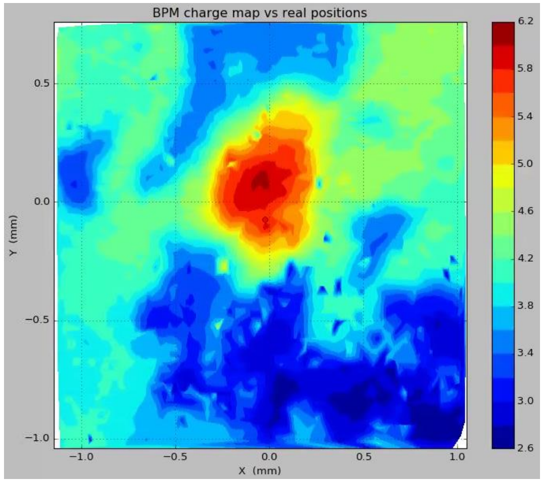
QE

QE map







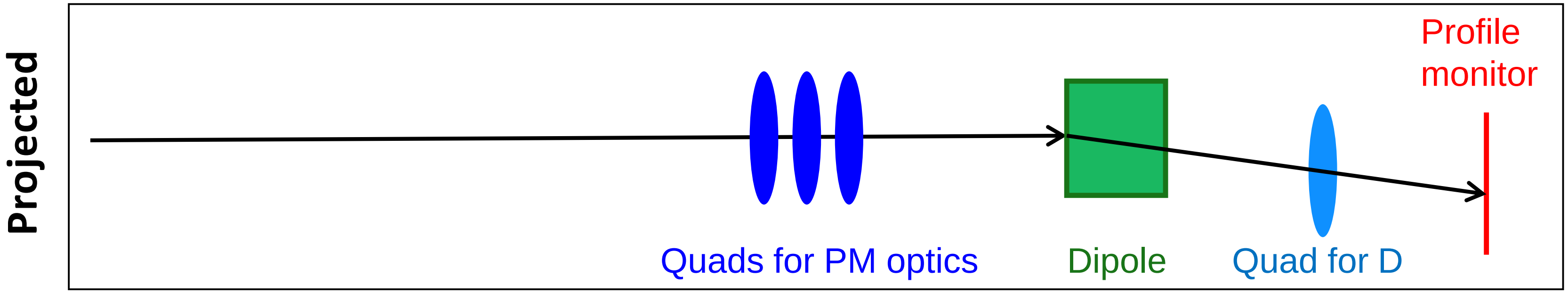


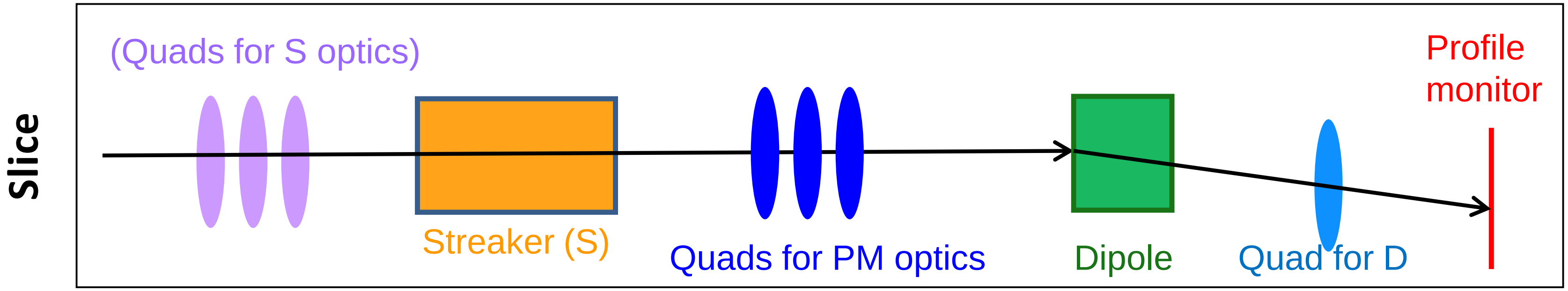
- Growing chamber equipped at PSI. Responsible: R. Ganter
- For long term data (in case we go away from Cs_2Te): where the other measurements are performed

https://conf.slac.stanford.edu/photocathode-physics-photoinjectors-2021/sites/ppp2021.conf.slac.stanford.edu/files/SessionC_Ganter_Presentation.pdf

Energy spread measurement

Measurement on the uncompressed beam, which may be enough





Streaking device (streaker):

The streaking can be done:

1. Using an rf transverse deflector: method known and routinely used
2. Introducing dispersion to an energy chirped beam: method known and usable
3. Using the transverse wakefield: to be studied at low energy (quadrupole may be an issue)
4. THz deflector: to be dimensioned and tested before it may be used

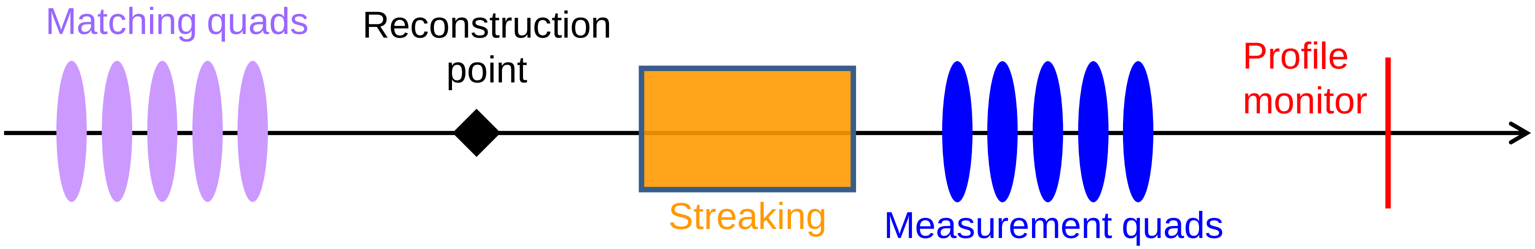
Beam emittance measurement

Measured ideally after at least one accelerating cavity (E~100 MeV), where the emittance is "frozen"

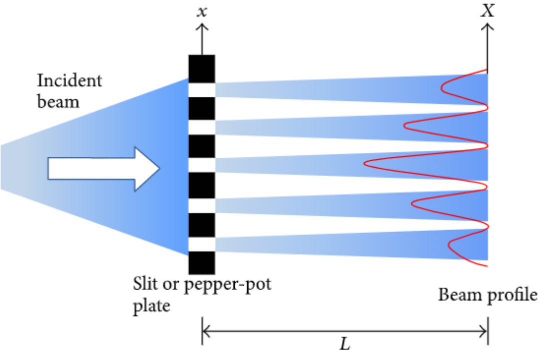
Quad scan

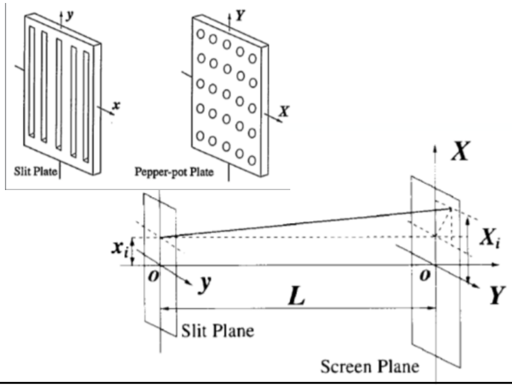
Sliced

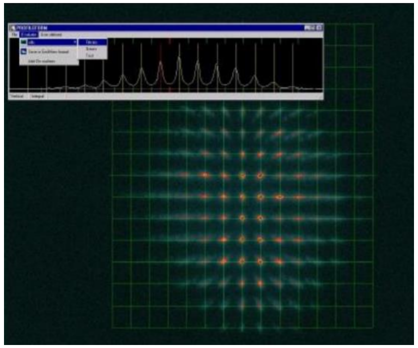
Projected



Pepper-pot



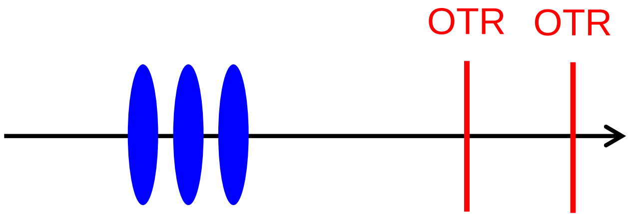




OTR

Happening when a charged beam passes through media (foil) with different permittivity.

Used in single or double foil setup.

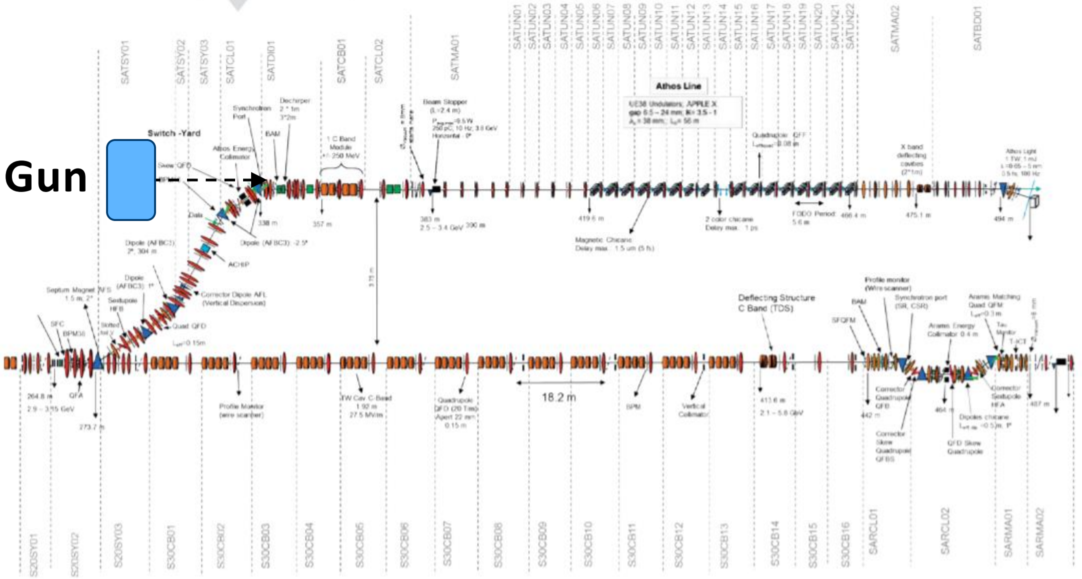


Pepper-pot: https://indico.cern.ch/event/664166/contributions/2795590/attachments/1661378/2661868/Pepperpot.pdf and https://www.researchgate.net/publication/313875930_STATUS_OF_THE_LOW-ENERGY_EMITTANCE_MEASUREMENT_SIMULATIONS_FOR_THE_SPARC_PROJECT/figures?lo=1 and https://www.hindawi.com/journals/stni/2016/4697247/

OTR-based: https://wiki.jlab.org/ciswiki/images/b/bd/Gitter_1992_603.pdf

Option 1: Athos branch

Fig. 2.6 Schematic of the SwissFEL Switch-Yard and Athos FEL (0.65 to 5 nm).



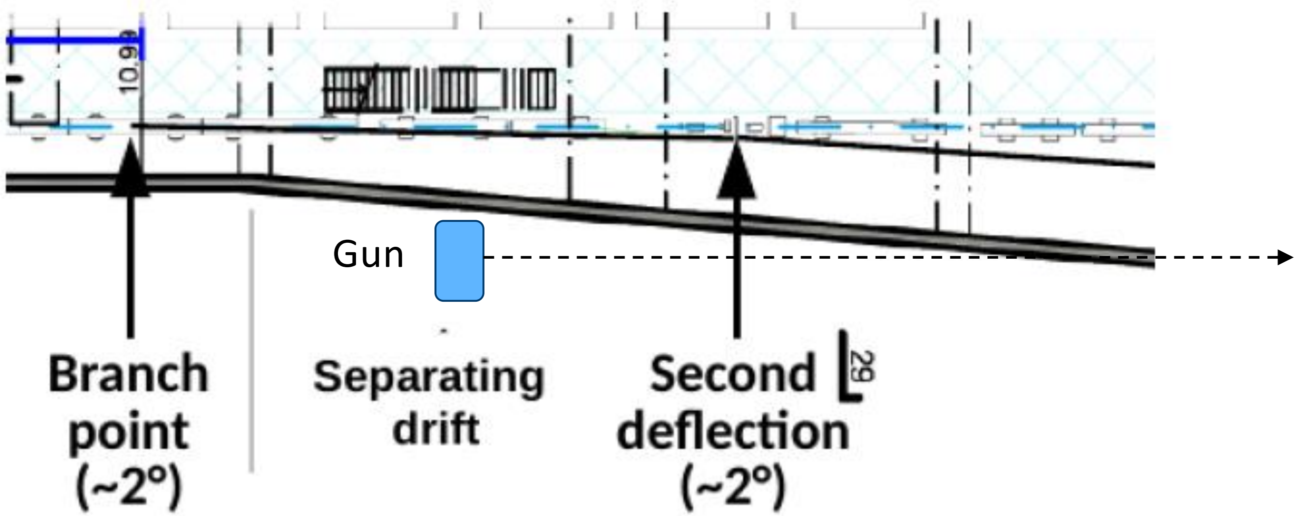
Pros:

- Hardware and technical system from SwissFEL usable
- HERO laser in the area
- C-band klystron relatively “in the area” (SATCB01)
- All the (uncompressed-projected-slice) beam measurements probably possible

Cons:

- Limited beam time: not compatible with users’ photon delivery to Athos and HERO project
- Possible space constraints
- Harmonics conversion or UV transport to be built

Option 2: Porthos branch



Pros:

- Hardware and technical system from SwissFEL Porthos usable (time schedule?)
- C-band klystron relatively "in the area"
- All the (uncompressed-projected) beam measurements probably possible

Cons:

- Limited beam time: not compatible with the HERO project
- Laser transport to be built
- Possible space constraints
- Harmonics conversion or UV transport to be built

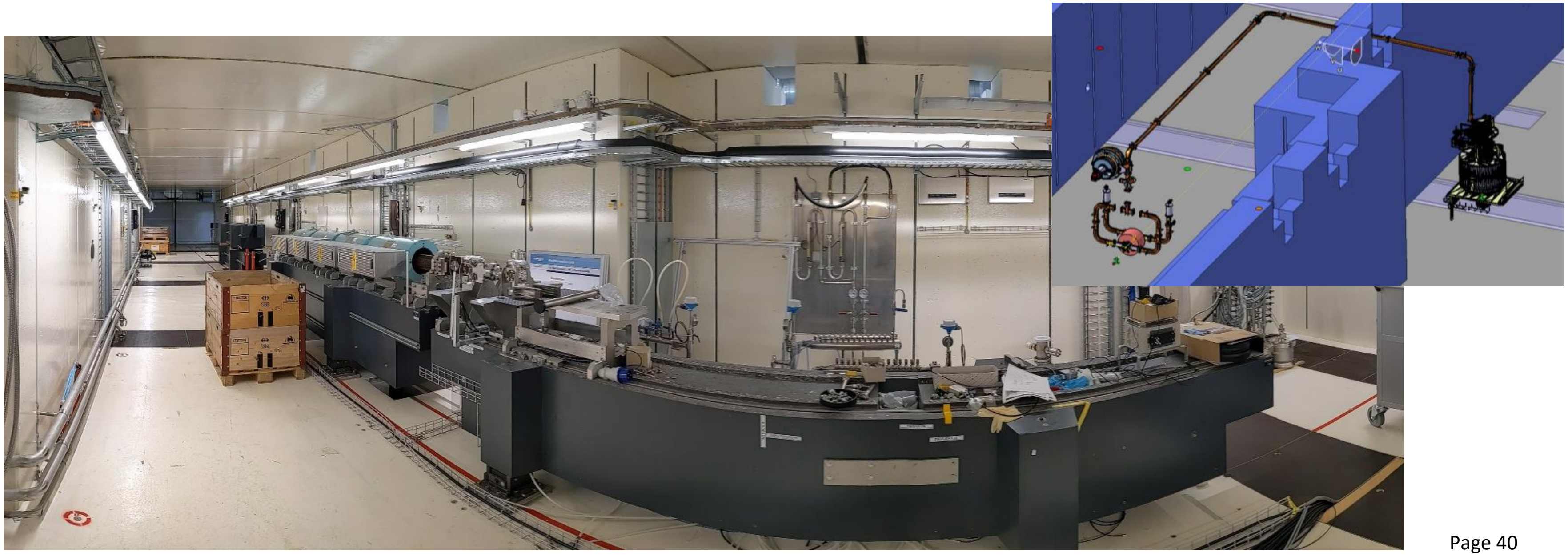
Option 3: test facility in WLHA

Pros:

- Basically unlimited beam time
- Possible synergies with other projects for Porthos and not only
- Other studies coming in the future

Cons:

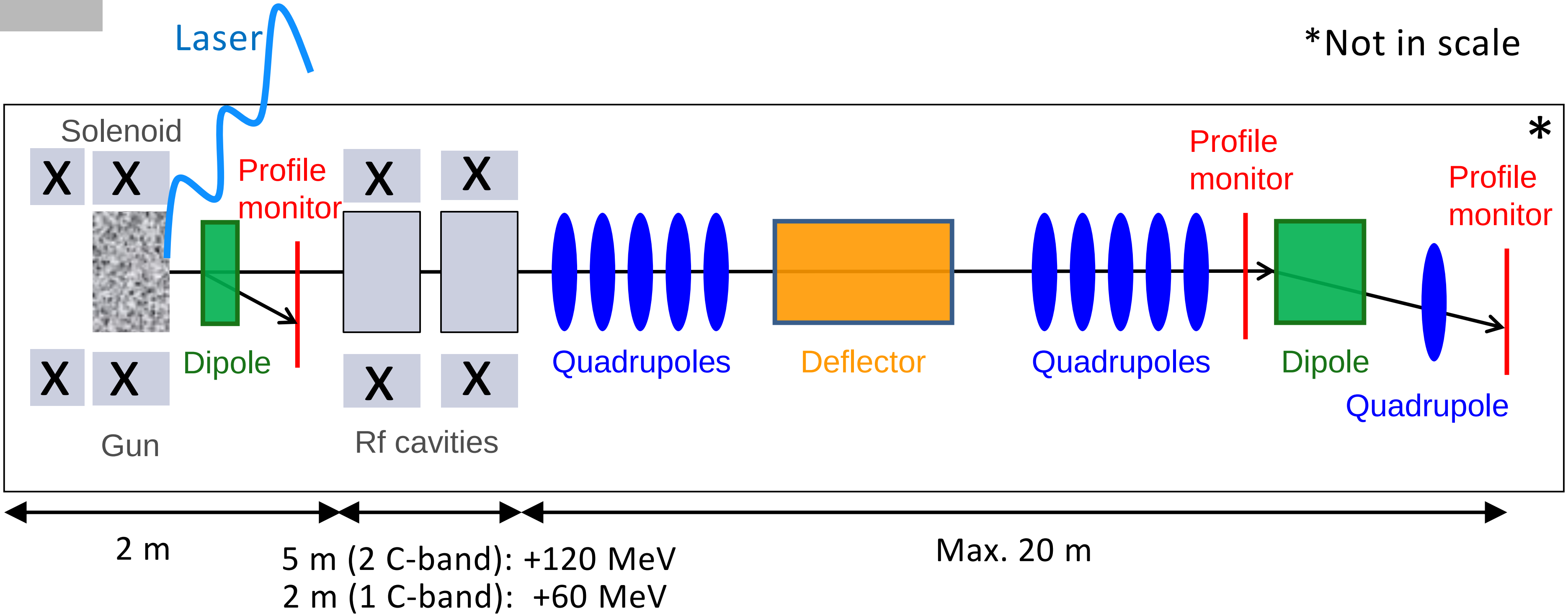
- Presently a rf test stand is foreseen
- To be designed a new facility: most probably gun, 1-2 rf stations to accelerate
- To be organized all to build and operate a test facility: timing, laser, controls, magnets, diagnostics, vacuum, safety, …



Schematic layout

To perform all the beam measurements the elements to be present are shown

On top of course all the systems: vacuum, synchronization, controls, …



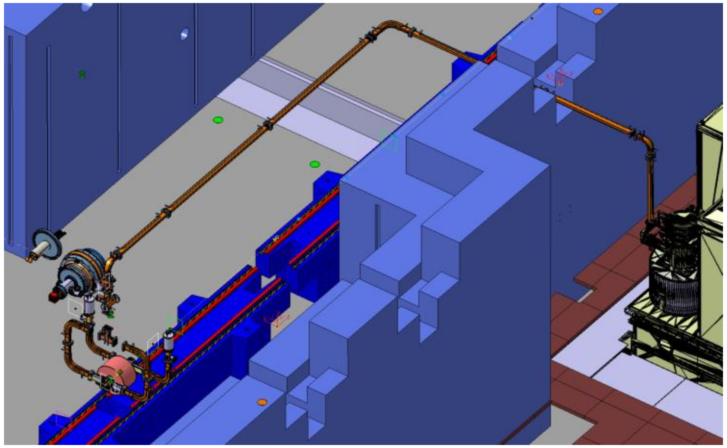
Total length 24 (27) m, final energy 72 (132) MeV with 1 (2) C-band cavities

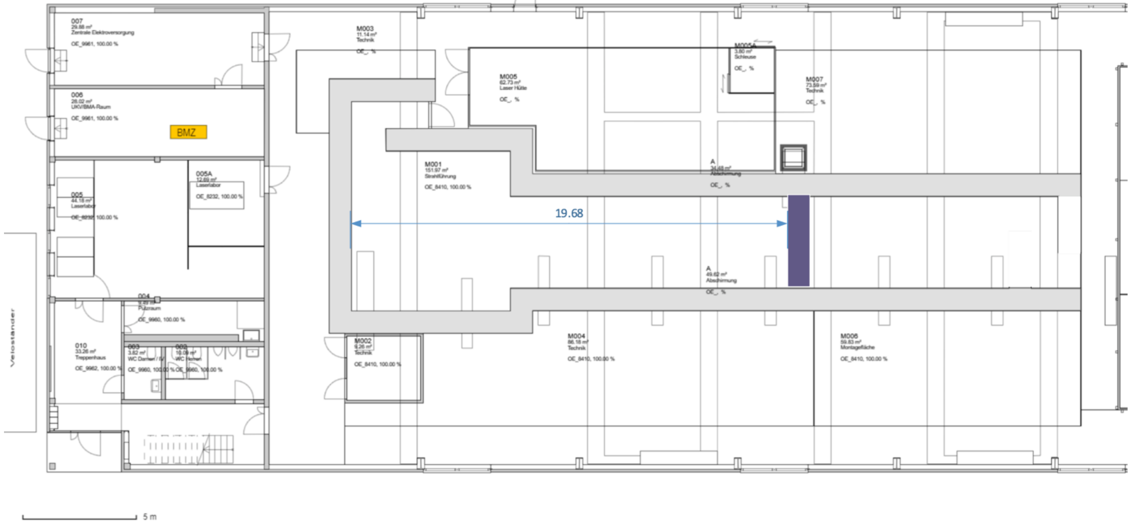
Length optimization to be done according to the HW possibilities

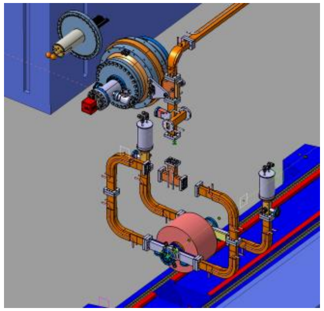
Status of the RF test stand (WLHA)

Courtesy of RF section

- **HV klystron modulator is routinely running** on C-band PSI loads (max power 50 MW)
- **Closure of the bunker**: documents under preparation to get permission from BAG
- **Waveguide network:** C-BOC and most of the RF components already at PSI



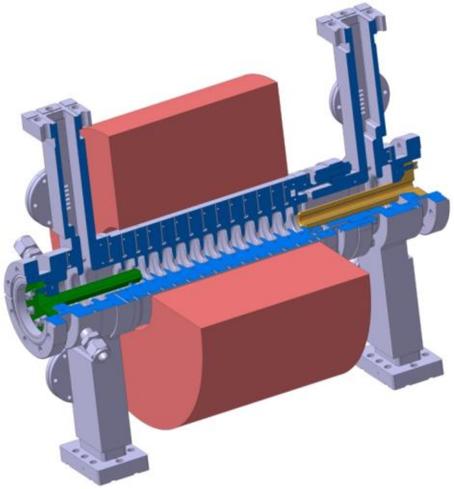




The bunker will be closed approximately at **19 m** from the wall to ensure that he bunker meets safety standards with respect to emergency exits.

The bunker already has all water and electrical facilities installed

Test facility in WLHA: possible synergies



- New acceleration schemes: among them for **Porthos**:
  WP R. Ischebeck
- THz diagnostics: way to diagnose the longitudinal beam properties in the facility itself for **Porthos**
- Cathode studies (green cathode, but not only): interest from **PSD** (laser group)
- Adaptive feed-backs of the laser: interest from **PSD** (laser group)
- Electron diffraction: some possible interest from the **BIO** division (J. Abrahams)?
- Gun test stand: INFN Frascati (**iFast**) and other projects studying new guns
- Detectors tests: some interest from **PSD** (B. Schmitt)?
- In general beamtime requests difficult to have granted at SwissFEL because sensibly impacting on the photon delivery: **several**

Conclusions

~~Conclusions~~ Discussion/comments/ideas

~~Conclusions~~ Discussion/comments/ideas

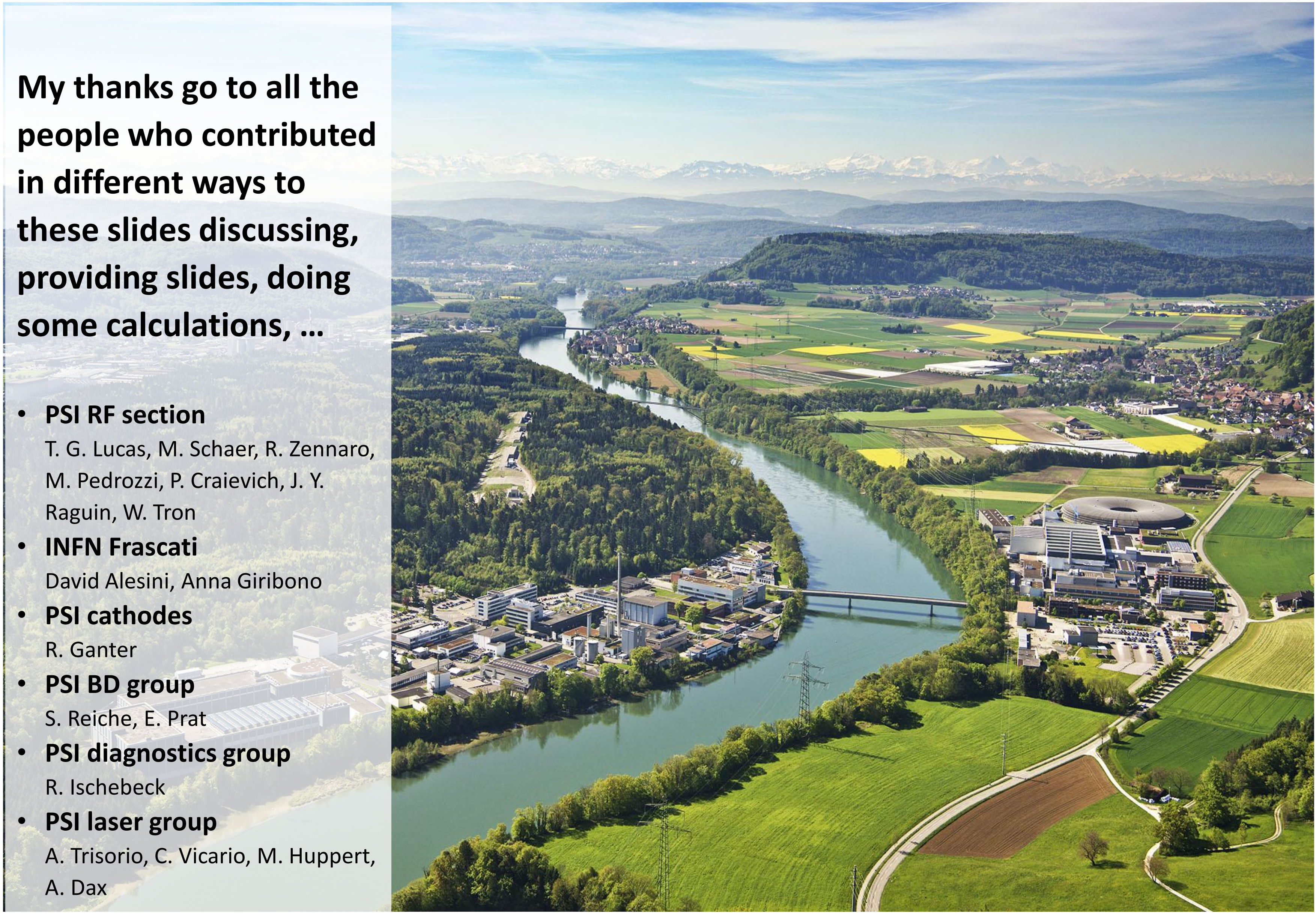
- SwissFEL presently already provides a very high brightness beam, but a further improvement may have a positive impact in Porthos, somehow in Aramis, and marginal in Athos

- Improvements relatively **no risk** and compatible with the Porthos **schedule**:
  - ⌂ Cathode roughness: co-evaporation
  - ⌂ High gradient rf guns: iFAST

- **Longer term** possible improvements:
  - ⌂ Green cathodes to further improve the laser
  - ⌂ Coating on a Cs_2Te cathode to reduce the intrinsic emittance

- Where to **test**?
  - ⌂ Is one of the SwissFEL branches an option?
  - ⌂ Is a new facility in WLHA a real possibility?
  - ⌂ Install in SwissFEL after doing the rf power tests in WLHA?

- Do we want to **further** optimize?



My thanks go to all the people who contributed in different ways to these slides discussing, providing slides, doing some calculations, …

- **PSI RF section**
  T. G. Lucas, M. Schaer, R. Zennaro, M. Pedrozzi, P. Craievich, J. Y. Raguin, W. Tron
- **INFN Frascati**
  David Alesini, Anna Giribono
- **PSI cathodes**
  R. Ganter
- **PSI BD group**
  S. Reiche, E. Prat
- **PSI diagnostics group**
  R. Ischebeck
- **PSI laser group**
  A. Trisorio, C. Vicario, M. Huppert, A. Dax

~~Conclusions~~ Discussion/comments/ideas

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SPARE SLIDES

Energy spread

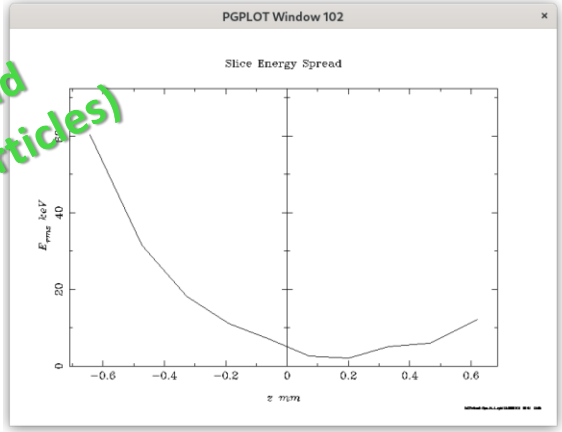
Courtesy of M. Schaer (C-band case)

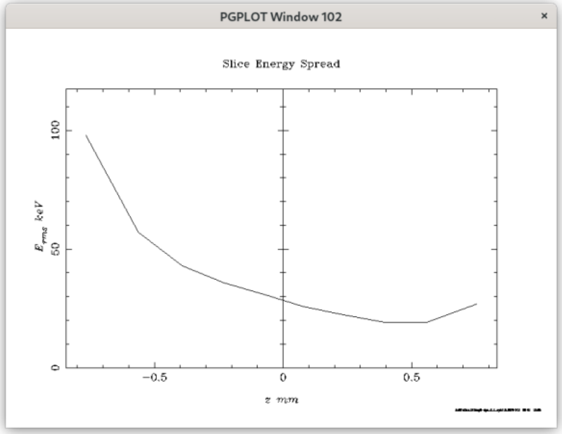
- Peak current = 61.1 A
- 60 deg phase advance / cell
- Max. accelerating gradient on-axis 135 MV/m
- Evaluation at z = 12.62 m, E = 139.4 MeV

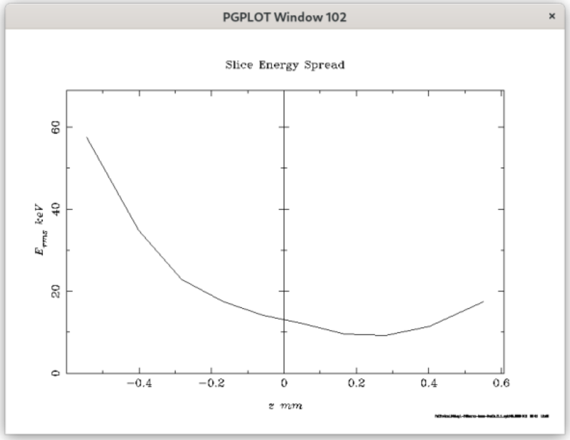
- Peak current = 40.8 A
- 120 deg phase advance / cell
- Max. gradient on-axis 135 MV/m
- Evaluation at z = 12.75m, E = 128.5 MeV

- Peak current = 56.3 A
- 120 deg phase advance / cell
- Max. gradient on-axis 200 MV/m
- Evaluation at z = 12.56m, E = 150.9 MeV

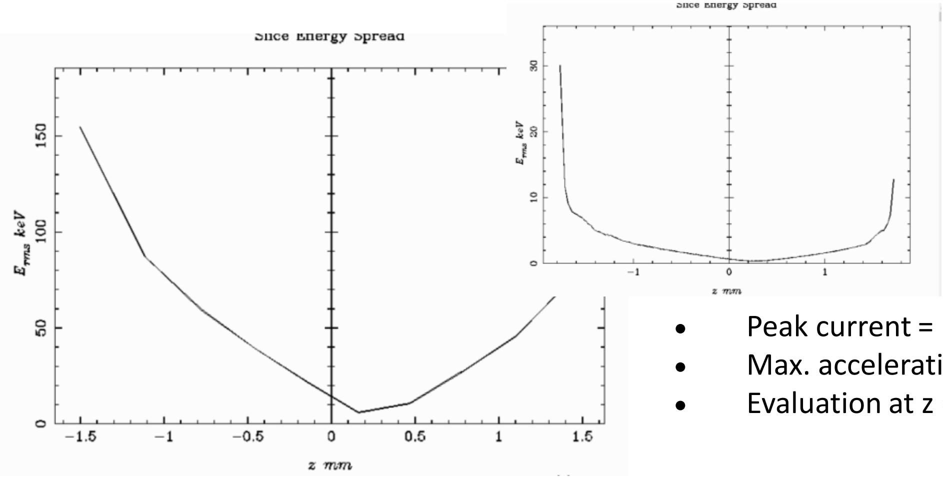
TW C-band (10k particles)







SwissFEL running S-band (200k particles)



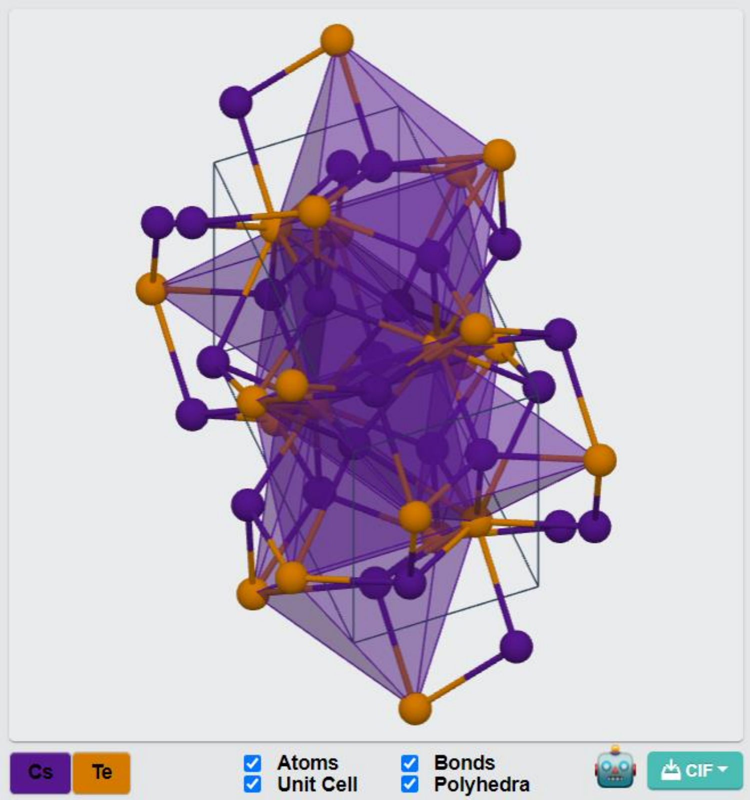
- Peak current = 20 A
- Max. accelerating gradient on-axis 100 MV/m
- Evaluation at z = 13.00 m, E = 137 MeV

Possible candidates to be determined

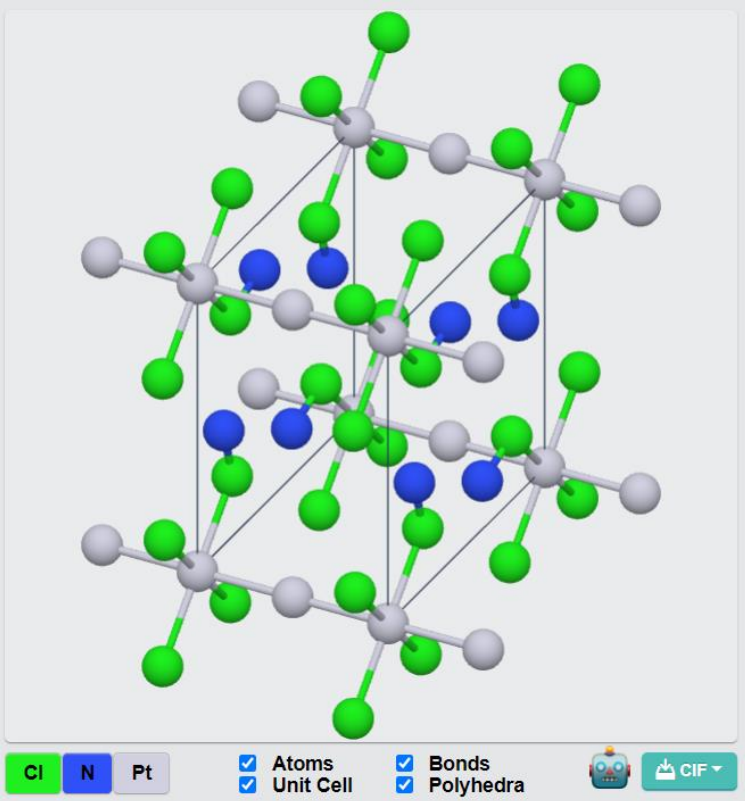
DOE Data Explorer

U.S. Department of Energy
Office of Scientific and Technical Information

Cs_2Te



$Pt(NCl)_2$



The structure is one-dimensional and consists of one Pt(NCl)2 ribbon oriented in the (0, 0, 1) direction

https://www.osti.gov/dataexplorer/search/

Beam emittance: considerations

For all the measurements:

- Consideration for the streaker element as for the DE spread measurement
- Better to perform the measurement when the beam emittance is “frozen”, i.e. at beam energy of the order of 100 MeV at least

Quad scan

- No phase space reconstructed, but tomography may be applied to have it
- Several quadrupoles and space required
- Method consolidated and routinely used in several facilities and also at SwissFEL

Pepper-pot

- Phase space reconstructed
- Less components required, less space necessary
- Method used in other facilities. It may be validated at SwissFEL

OTR

- Less hardware and space required
- Some optimizations to be done to minimize errors
- Less used method in other facilities. It must be tested at SwissFEL