Light Sources in Europe: Case Study
The COMPACT LIGHT Collaboration

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Outline

- Light Source an innovative accelerator tool
- Light Source Applications
- Light Source facilities in Europe
- The **Compact Light** Collaboration
- From CLIC Technology to a 4th Generation light source
- The Greek participation

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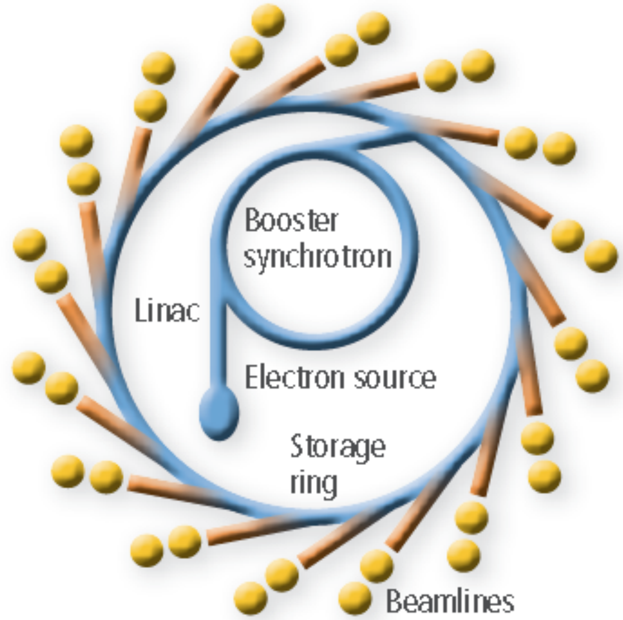
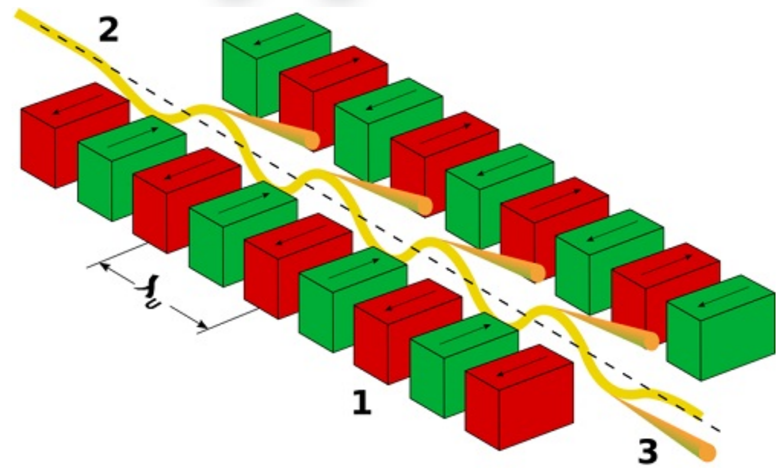
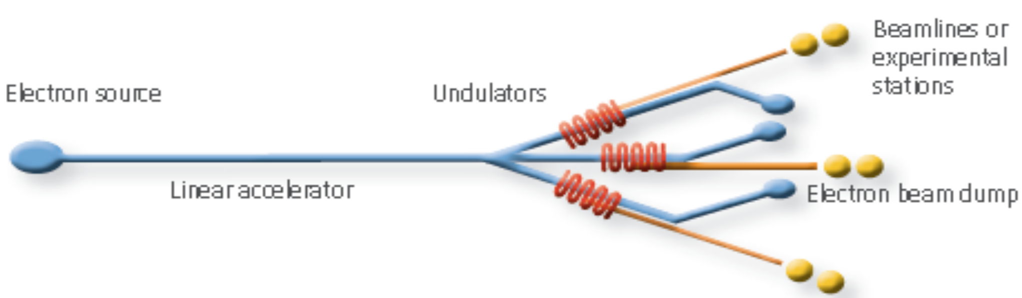
Light Source an innovative accelerator tool

- **Fast electrons** at nearly the speed of light cross a **magnetic field** on their way, are deflected and generate **bright**, well collimated **light** tangentially to their path.
- Firstly, observed on a **General Electric synchrotron** accelerator in **1947** and the light was called **synchrotron radiation**.
- For decades, this effect produces **high-intensity radiation** in a wide spectral range from the **far infrared** tc **hard X-rays**.
- Modern **synchrotron radiation sources** use a series of tens (or even hundreds) of magnets with alternating field, called **undulator**.
- The electrons generate light which overlaps and interferes constructively for certain wavelengths leading to nearly **monochromatic light** emitted in a **narrow cone**.







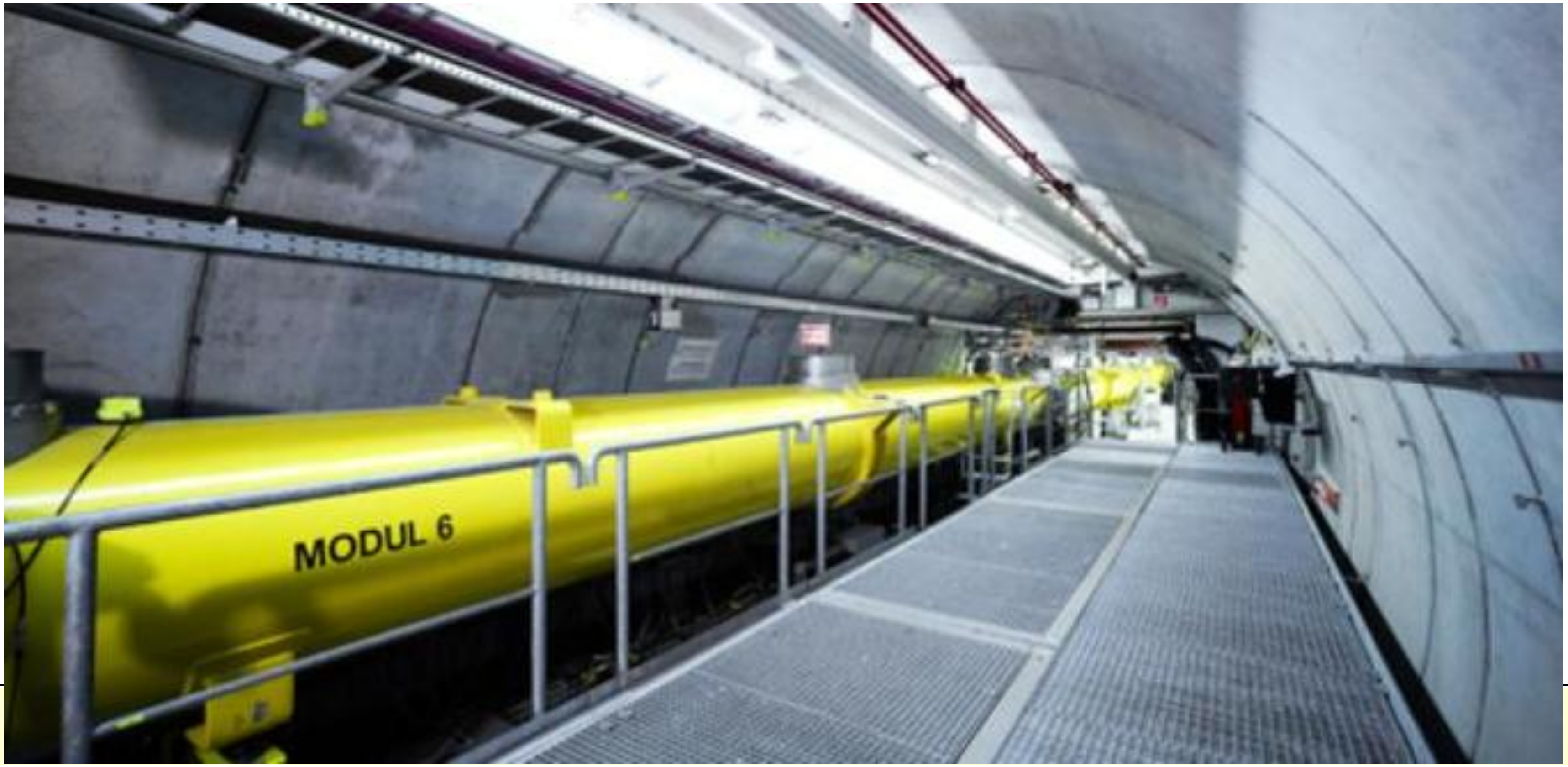
1: magnets
2: electron beam entering from the upper left
3: laser light exiting to the lower right

Light Source an innovative accelerator tool

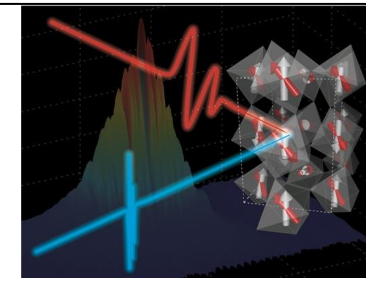
The **Free Electron Laser (FEL)** makes use of the physics of the undulator, **amplifying resonant radiation**.

There were calculated that "**finite gain** is available from **the far-infrared** through the further possibility of partially coherent radiation sources in the **ultraviolet** and **X-ray** regions to beyond **10 keV**".

The **undulator** is **very long** and a better quality **electron beam** of **density** and **emittance** with millions of electrons **radiate in phase**, leading to a tremendous **gain** and **ultrashort pulses** covering a huge spectral range to **hard X-rays**, producing more powerful than what all other types of **X-ray sources**.

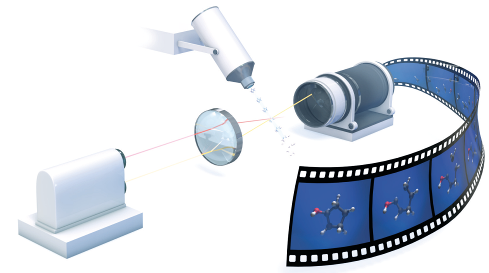


Light Source Applications



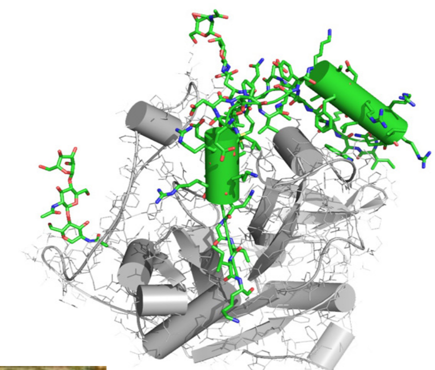
Quantum Materials

Quantum materials are new, promising materials such as high-temperature superconductors, topological insulators and multiferroics, which have novel and unusual electronic properties.



Femtochemistry

Femtochemistry is concerned with the study of chemical reactions at their natural atomic, femtosecond time scale in order to control - the atomic motions.



Serial Femtosecond Crystallography

SFX is a method whereby molecular structures can be determined by collecting a large number of single shot diffraction patterns from a stream of nanocrystals.

Cultural Heritage and Archeology studies

Hidden paintings in V. Van Gonh’s master pieces. Ancient items material analysis.

Health, Environment, Energy, Food, Engineering & Manufacturing

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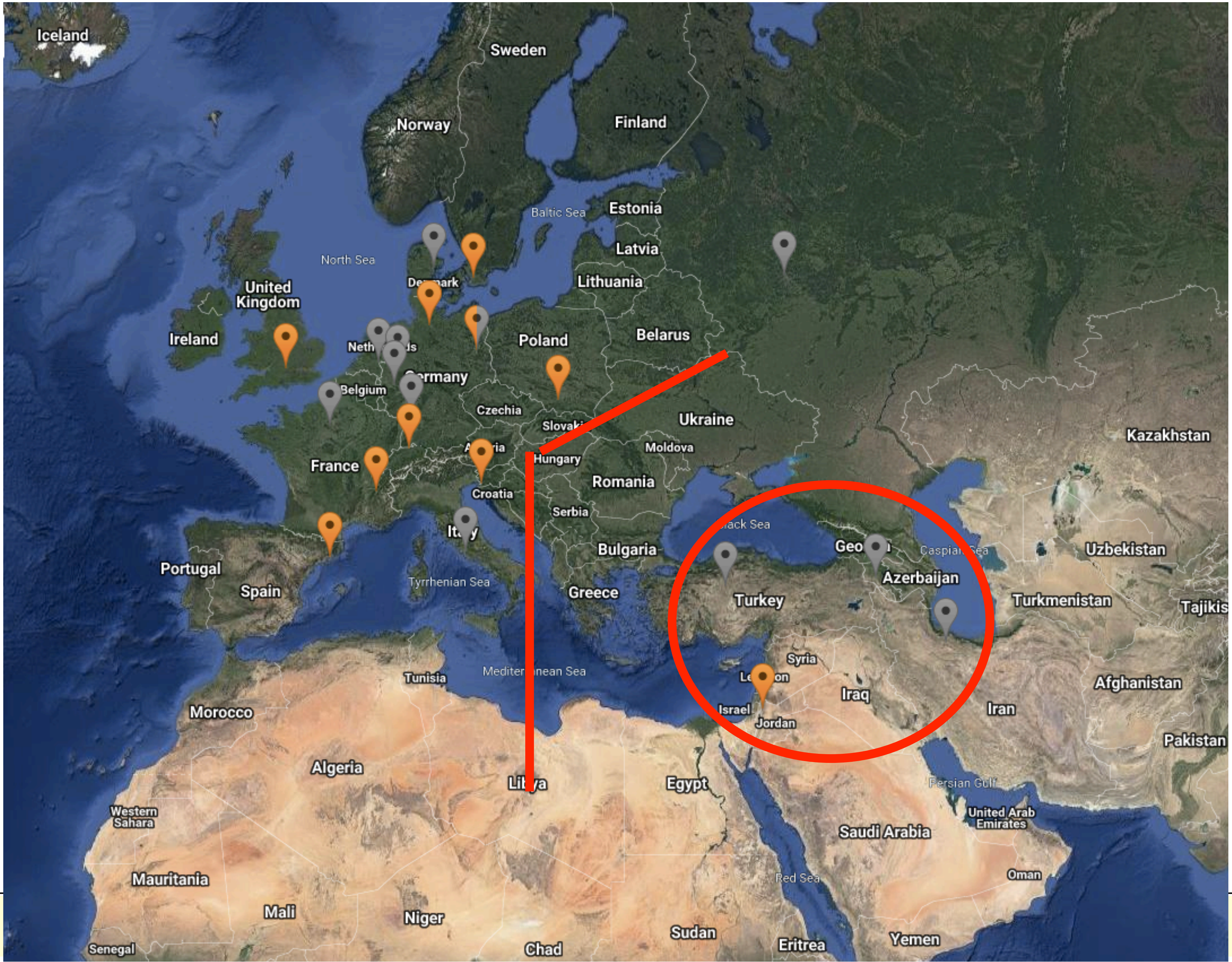
Light Source facilities in Europe

LEAPS League of European Accelerator-based Photon Sources

FELs

Light Source facilities in Europe and Middle East



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The **Compact Light** Collaboration – List of Participants

Compact

Participant		Organisation Name	Country
1	ST (Coord.)	Elettra – Sincrotrone Trieste S.C.p.A.	Italy
2	CERN	CERN - European Organization for Nuclear Research	International
3	STFC	Science and Technology Facilities Council – Daresbury Laboratory	United Kingdom
4	SINAP	Shanghai Inst. of Applied Physics, Chinese Academy of Sciences	China
5	IASA	Institute of Accelerating Systems and Applications	Greece
6	UU	Uppsala Universitet	Sweden
7	UoM	The University of Melbourne	Australia
8	ANSTO	Australian Nuclear Science and Tecnology Organisation	Australia
9	UA-IAT	Ankara University Institute of Accelerator Technologies	Turkey
10	ULANC	Lancaster University	United Kingdom
11	VDL ETG	VDL Enabling Technology Group Eindhoven BV	Netherlands
12	TU/e	Technische Universiteit Eindhoven	Netherlands
13	INFN	Istituto Nazionale di Fisica Nucleare	Italy
14	Kyma	Kyma S.r.l.	Italy
15	SAPIENZA	University of Rome "La Sapienza"	Italy
16	ENEA	Agenzia Naz. per le Nuove Tecnologie, l'Energia e lo Sviluppo Economico Sostenibile	Italy
17	ALBA-CELLS	Consorcio para la Construccion Equipamiento y Explotacion del Lab. de Luz Sincrotron	Spain
18	CNRS	Centre National de la Recherche Scientifique CNRS	France
19	KIT	Karlsruher Institut für Technologie	Germany
20	PSI	Paul Scherrer Institut PSI	Switzerland
21	CSIC	Agencia Estatal Consejo Superior de Investigaciones Científicias	Spain
22	UH/HIP	University of Helsinki - Helsinki Institute of Physics	Finland
23	VU	VU University Amsterdam	Netherlands
24	USTR	University of Strathclyde	United Kingdom

Third Parties		Organisation Name	Country
AP1	OSLO	Universitetet i Oslo - University of Oslo	Norway
AP2	ARCNL	Advanced Research Center for Nanolithography	Netherlands
AP3	NTUA	National Technical University of Athens	Greece
AP4	AUEB	Athens University Economics & Business	Greece

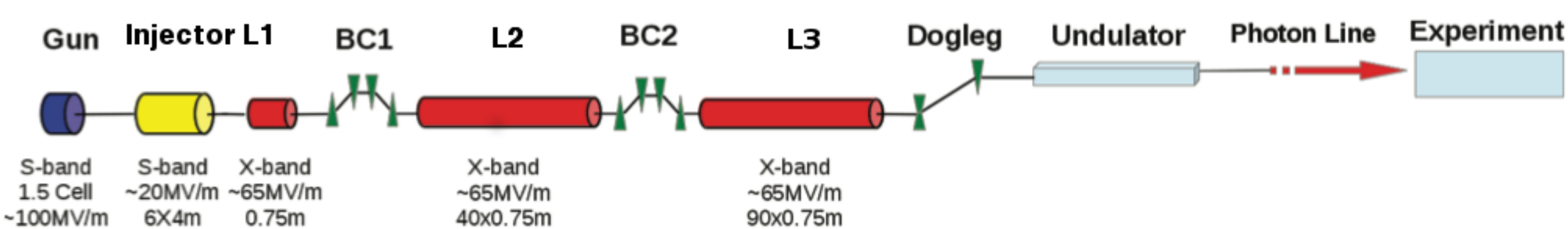
http://compact-light.web.cern.ch

H2020: INFRADEV-01-2017

01-01-2018

36 Months

Italy	5
Netherl.	3+1
UK	3
Spain	2
Australia	2
China	1
Greece	1+2
Sweden	1
Turkey	1
France	1
Germany	1
Switzerl.	1
Finland	1
Norway	0+1
Internat.	1



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Aims and Objectives I

"The possibility of producing **low charge** (pC range), **ultra-short** (sub-micrometer), electron bunches with **small emittance** and **high brightness**, opens new possibilities to design and build **compact, lower cost FELs**, to produce high intensity, femtosecond long, coherent X-ray pulses in a wide wavelength range".

C. Pellegrini, "Cheaper, Smaller, Better"

With Compact Light we plan to design **a Hard X-ray Facility** using the very latest concepts for:

a. High brightness electron photo-injectors

b. Very high gradient accelerating structures

c. Novel short period undulators

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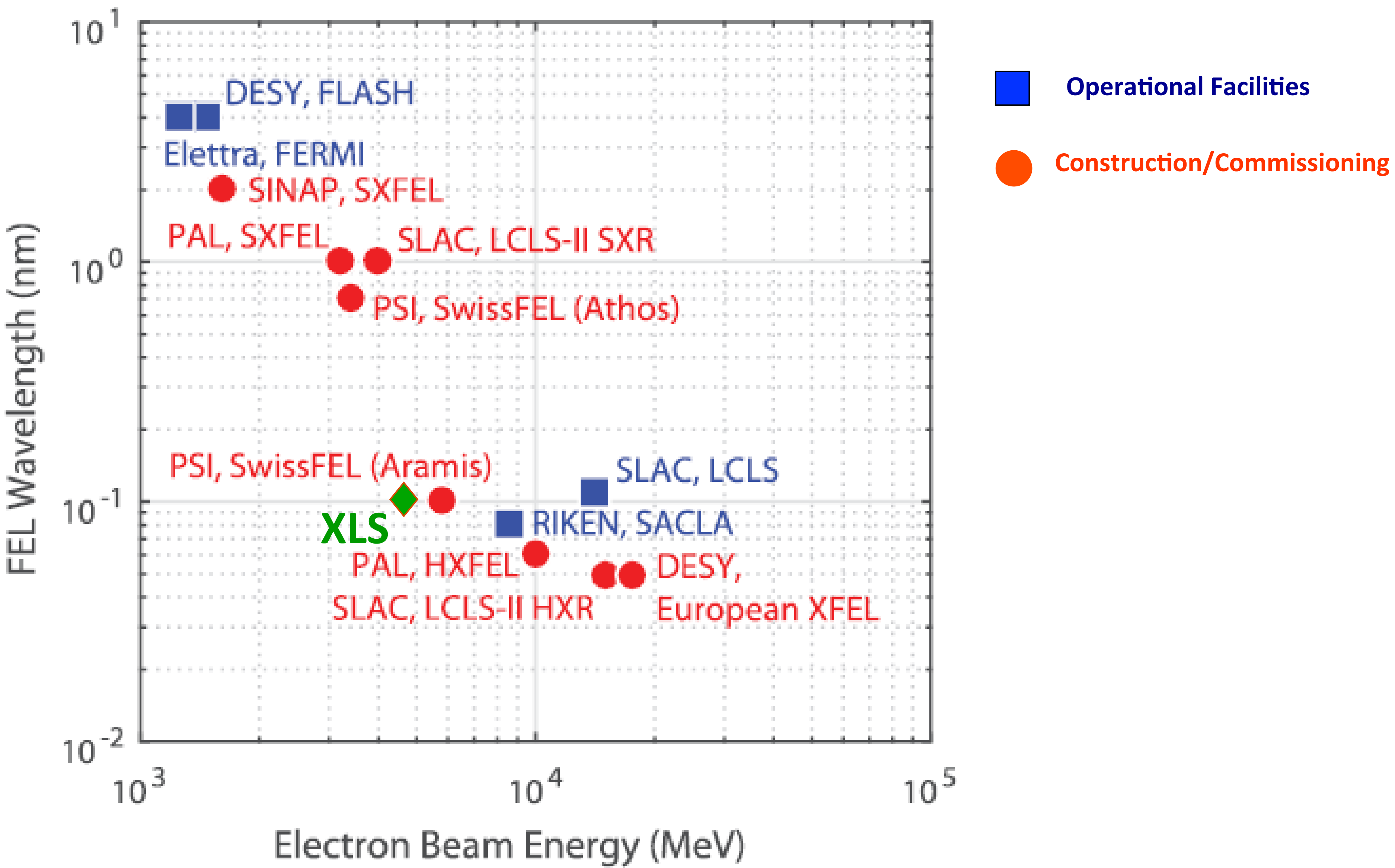
Aims and Objectives II

The New Facility, compared with Current Facilities, will benefit from:

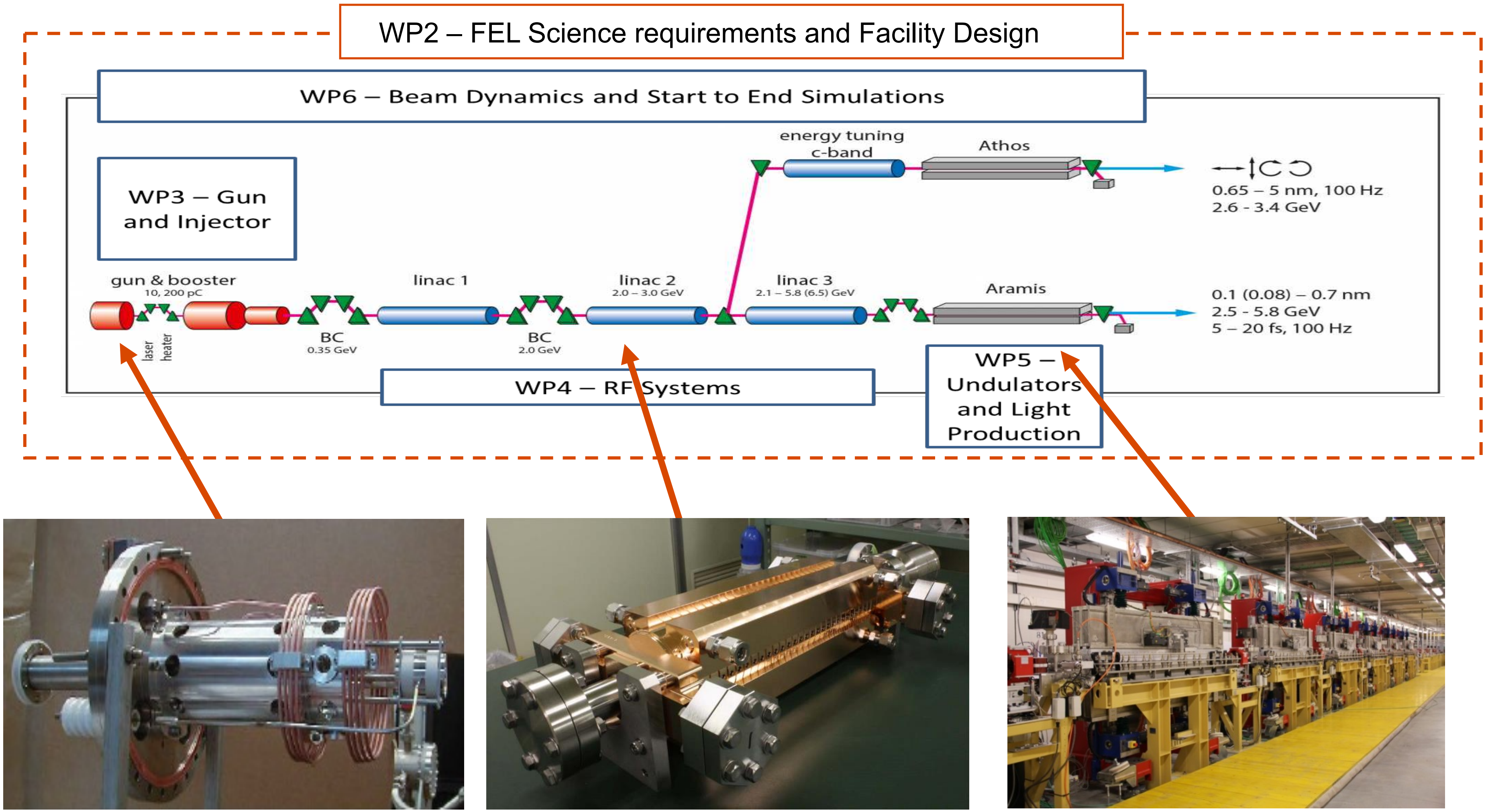
i. A lower electron **beam energy**, due to the **enhanced undulator** performance.
ii. Being significantly **more compact** due to lower energy and **high gradient structures**.
iii. Having a much **lower electrical power demand** than current facilities.
iv. Having much **lower construction and running costs**.

This will **facilitate** the widespread **development of X-ray FEL** facilities across Europe and beyond, by making their **construction** and **operation costs** more **affordable** through an **optimum combination** of emerging and **innovative accelerator technologies**.

Compact Light Project and other X-FELs



From CLIC Technology and other facilities to XLS



Bring together technology advances in key accelerator systems for XFEL from CLIC

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WP3: Gun & Injector

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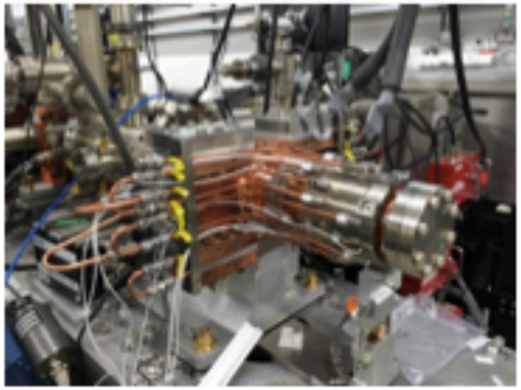
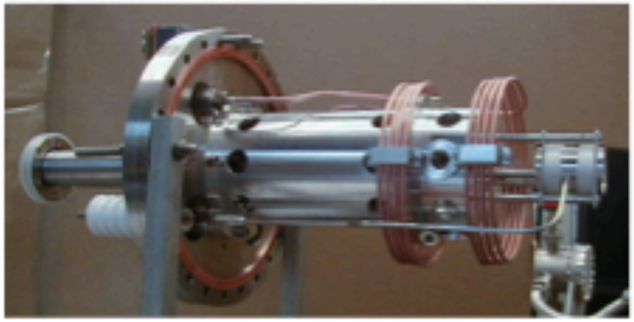
Tasks:

Review/Design **State of the art e-Gun/Injector** (S, C, X-band) and pick the best for XLS

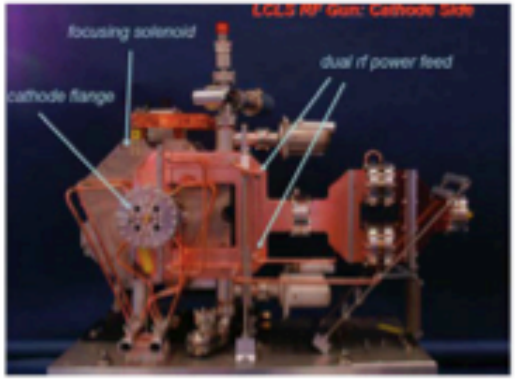
Develop of **novel high-repetition rate e-**gun/injector (with K-band linearizer)



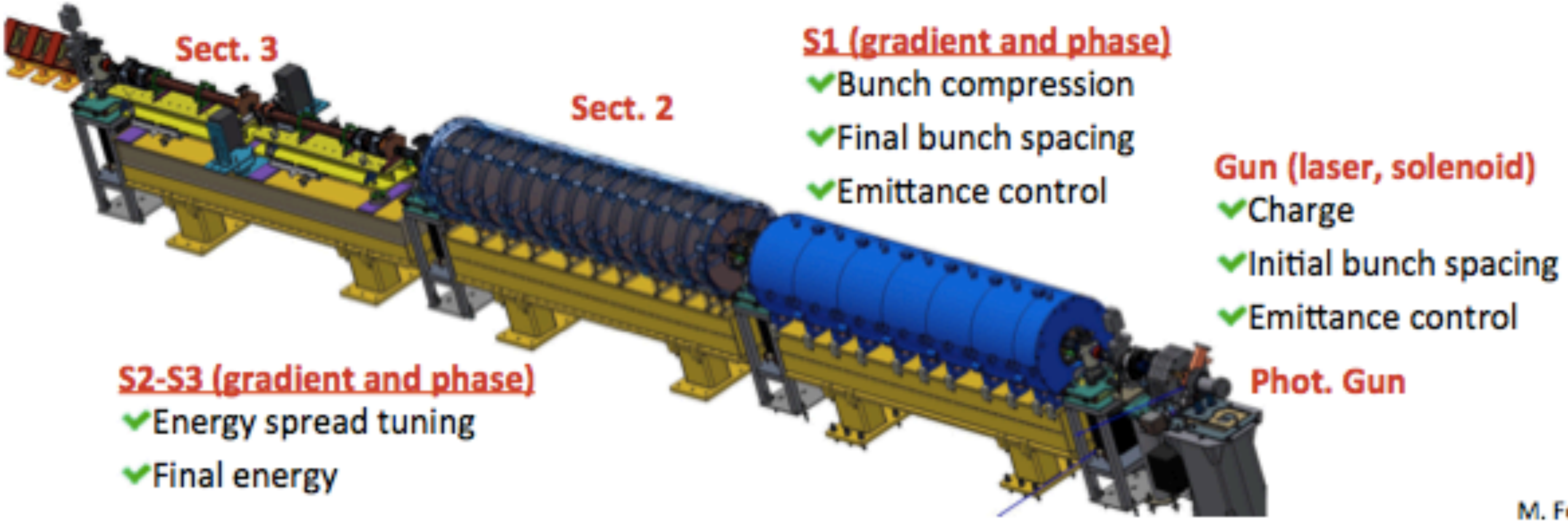
400Hz S-band rf gun in CLARA



Ultra-low emittance electron source, TU/e



LCLS S-band rf gun

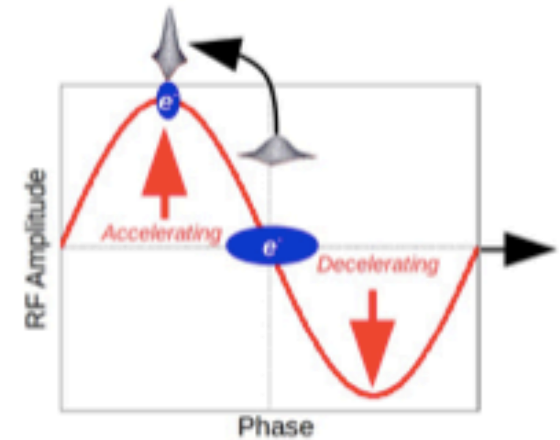


M. Ferrario

Ultra-short electron beam production with Velocity Bunching

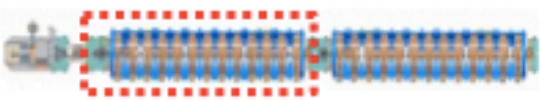
Current demands require high current beams

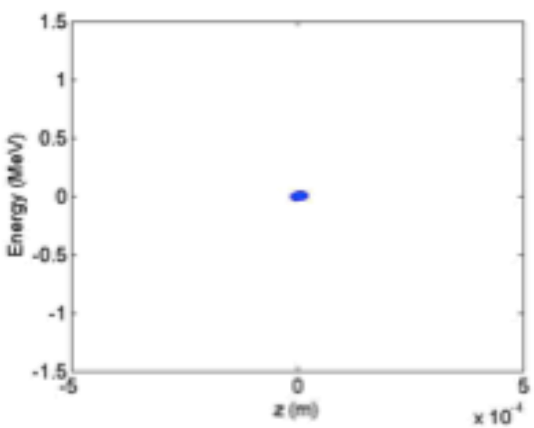
- ✔ *Advanced radiation sources: high peak currents (FEL), short beams (broadband THz radiation).*

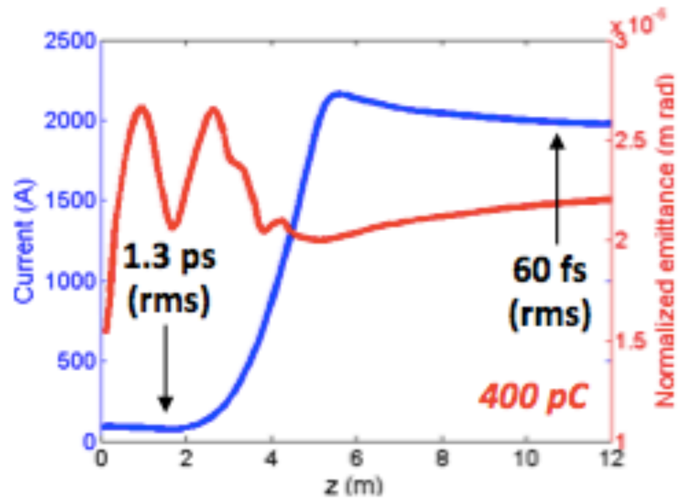


Velocity bunching @ SPARC_LAB

- ✔ *RF structure embedded in solenoid fields for* ***emittance compensation***







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WP4: RF Systems

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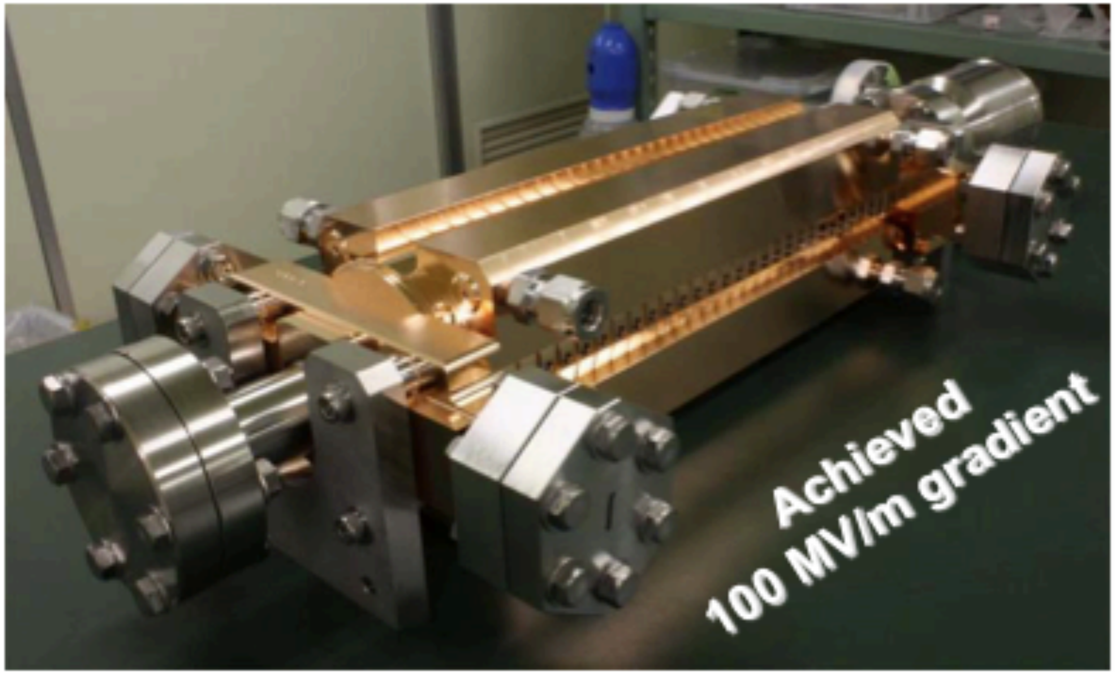
Linac gradients for most recent X-ray FELs

European XFEL (Germany)	24 MV/m	Superconducting L-band
Swiss FEL (Switzerland)	28 MV/m	Normal-conducting C-band
SACLA (Japan)	35 MV/m	Normal-conducting C-band

CERN accel. structure:

- Normal-conducting X-band
- Gradient 100 MV/m
- Input power ≈50 MW
- Pulse length ≈200 ns
- Repetition rate 50 Hz



XLS target: 65-70 MV/m

W. Wuensch

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XLS Accelerator Structure optimization

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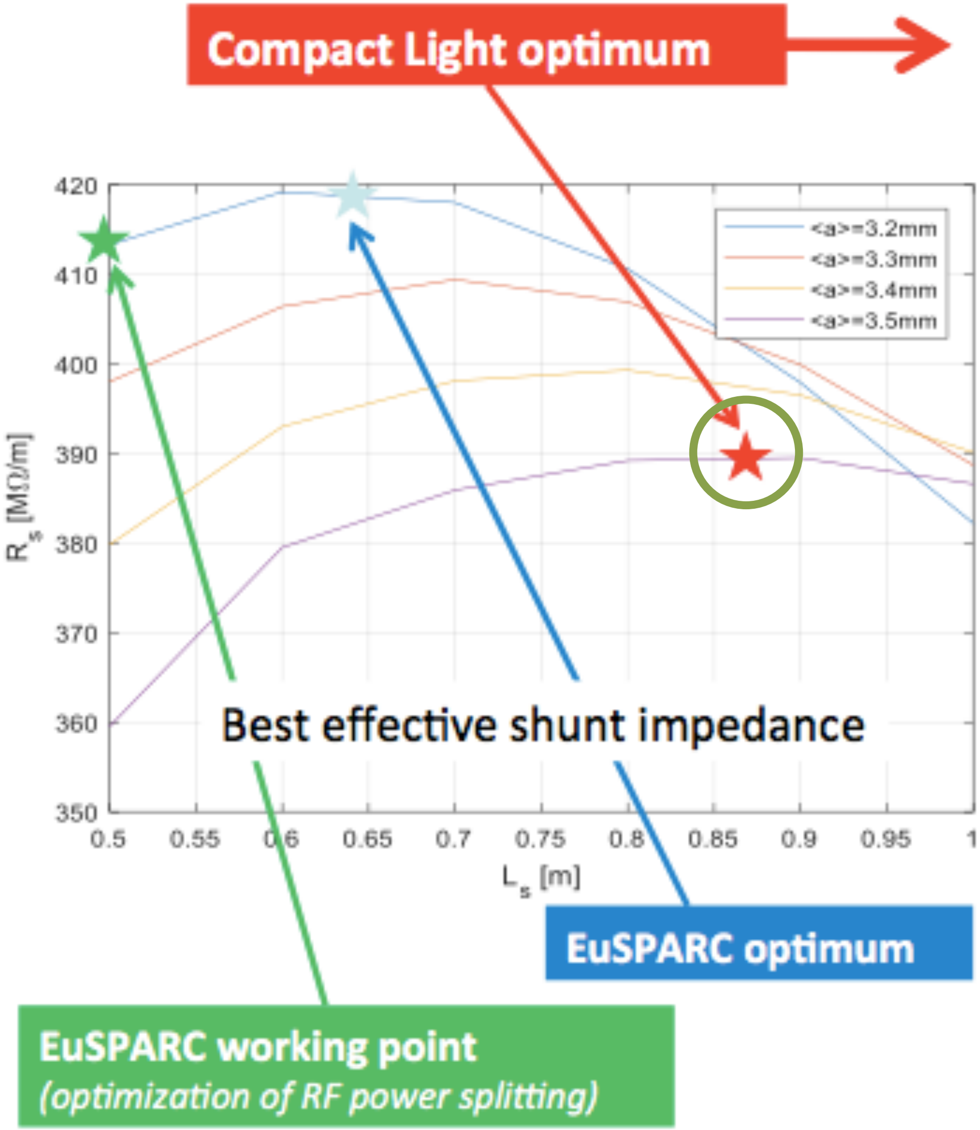
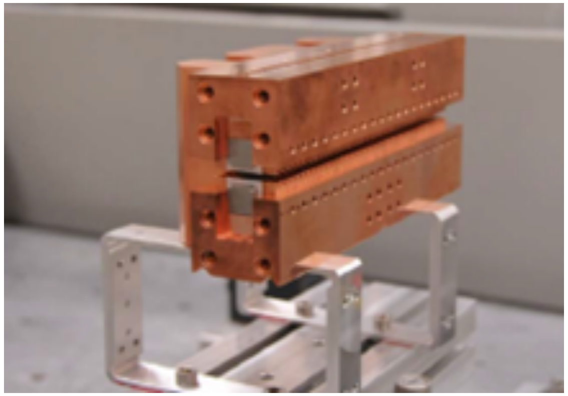


Freq. of 2π/3 mode [GHz]	**11.9942**
Average iris radius <a> [mm]	3.5
Total length of the TW structure L_s [m]	0.9
RF pulse [μs]	1.5
Average gradient <G> [MV/m]	**65**
Linac Energy gain E_{gain} [GeV]	4.5
Linac active length L_{act} [m]	69.2
Unloaded SLED Q-factor Q_0	180.000
External SLED Q-factor Q_E	21400
Iris radius a [mm]	4.3-2.7
Group velocity v_g [%]	4.5-1.0
Effective shunt Imp. R_s [M?/m]	**389**
Filling time t_f [ns]	140
Input power per structure P_{k_s} [MW]	9.8
Structures per module N_m (input power per module P_{k_m} [MW])	**4 (39)**
Total number of structures N_{tot}	**80**
Total number of klystrons N_k	**20**

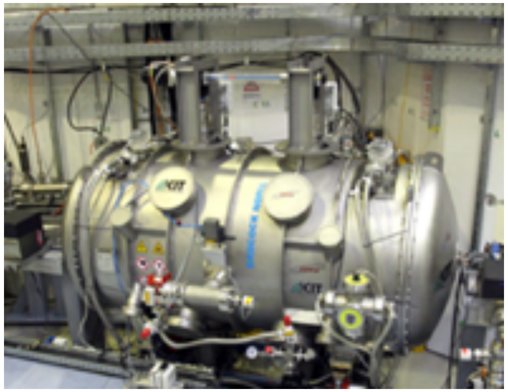
WP5: Undulators and Light production

Comparative studies of “ambitious” undulators on the timescale of 4-5 years: eg. cryo permanent-magnet, super-conductive undulators, etc. <== **work under development**



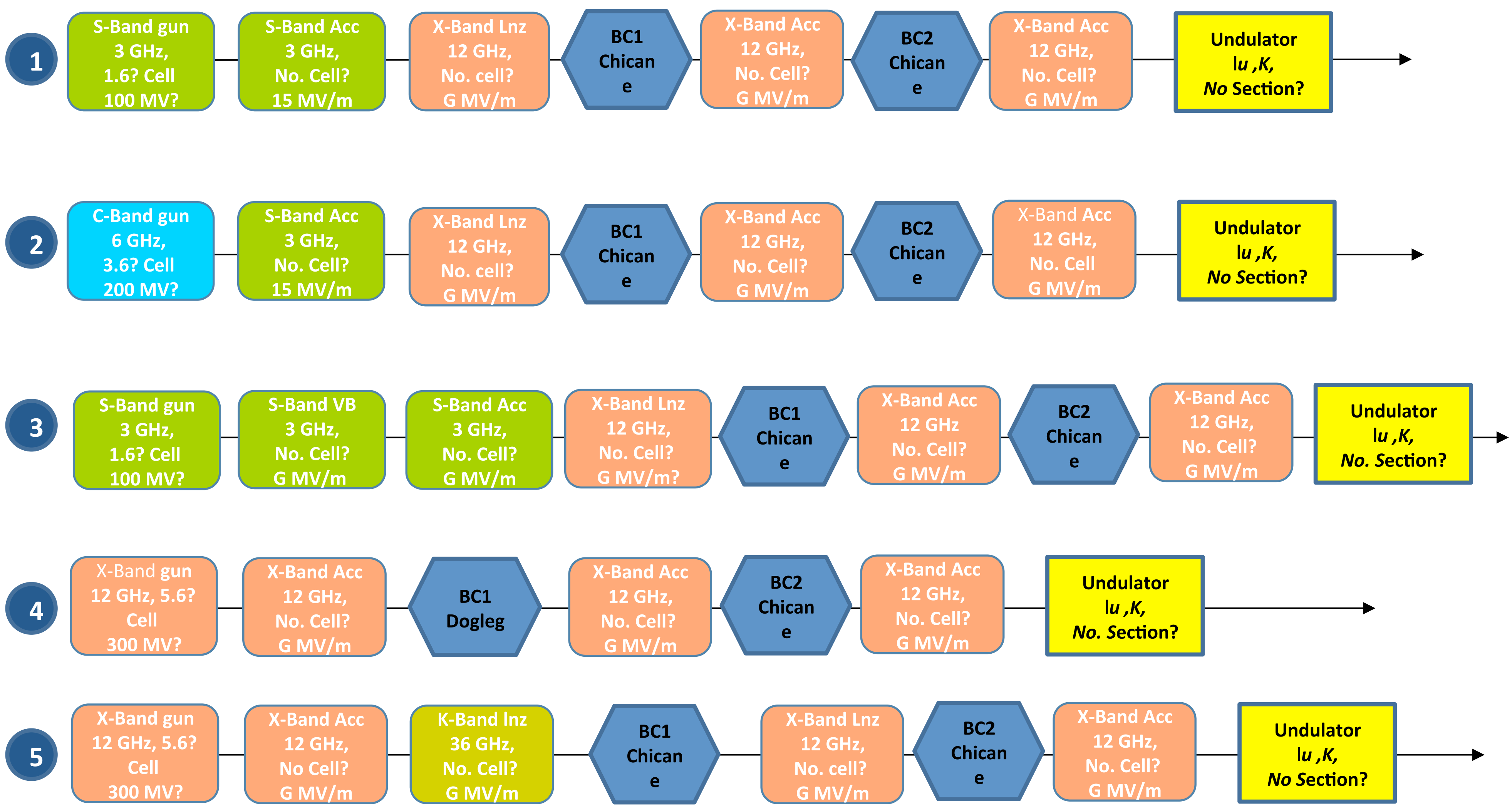
Undulator
HZB/UCLA

ENEA-INFN



S.C. Undulator KIT

S2E simulations and FEL performance studies



The Greek TEAM participation

IASA/NTUA: R. Koutitsa, K. Tzanetou, I. Telali, ENG

ESS/NTUA: N. Gazis, E. Tanke, E. Trachanas

AUEB: T. Apostolopoulos, K. Pramatari, A. Karagiannaki

WP1:	Co-coordination of the project	IASA
WP3:	Laser/Photocathode (coordinator)	IASA/NTUA
	e-Gun, Injector mechanical design	ESS/NTUA
WP6:	Beam dynamics simulation	NTUA
WP7:	Cost & Risk Analysis	AUEB
	Transfer Technology to industry	AUEB
	Data Management Planning	IASA/NTUA

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 cathode surface (like Cs_2Te) gets contaminated in the atmosphere during installation, leading to unpredictable quantum efficiency (QE) fluctuations.

Types and Criteria of Photocathodes

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

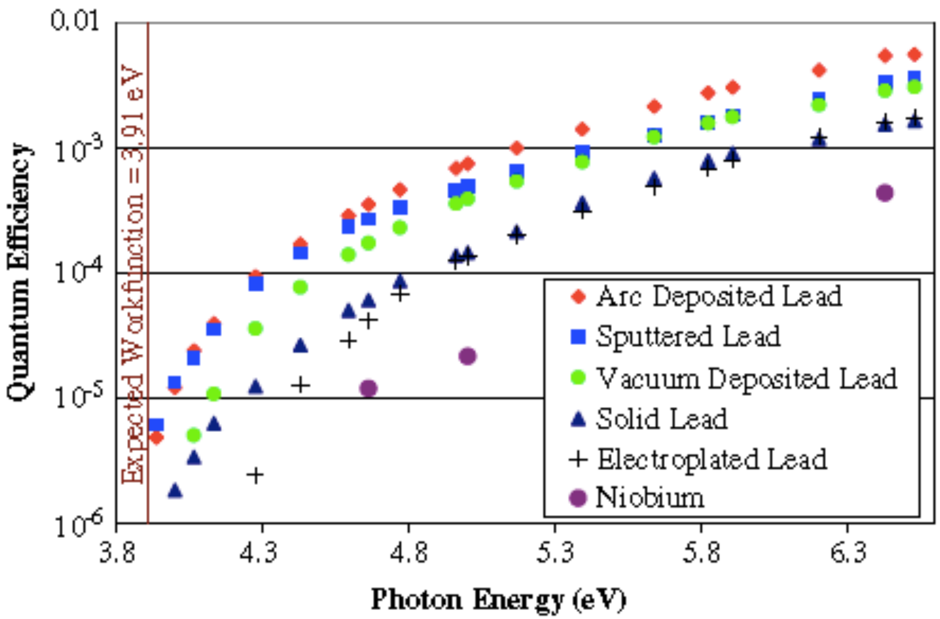
Semi-conductors (GaAs, Cs_2Te, K_2CsSb,GaN) – high efficiency, slower time response, sensitive to contamination, visible/IR lasers

SELECTION CRITERIA

- High Quantum efficiency
- High Robustness
- Low intrinsic emittance
- Fast response time
- Long time operation

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

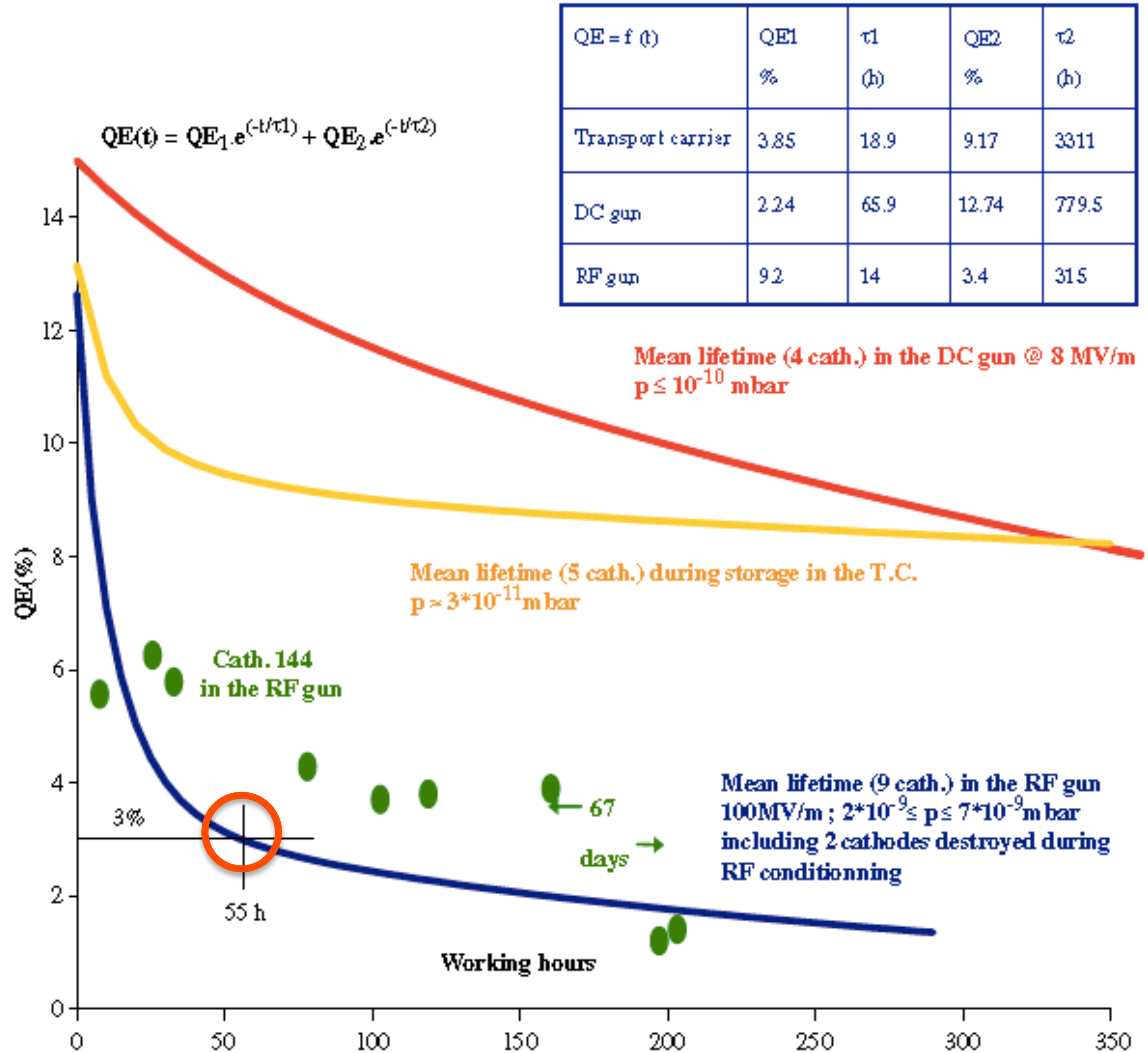
Pb/Nb → Super-conducting

Cs_2Te Photocathodes, 10% QE at 266nm

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

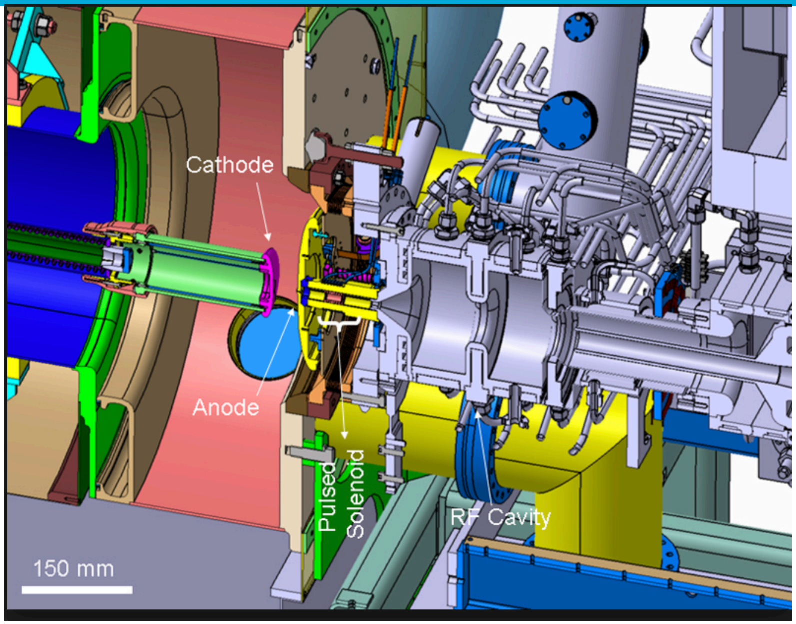
- High QE in UV
- NC RF-injector
- High Acc. Gradient
- 4 nC/pulse delivered, ~1mA current
- High work function ➔ UV laser

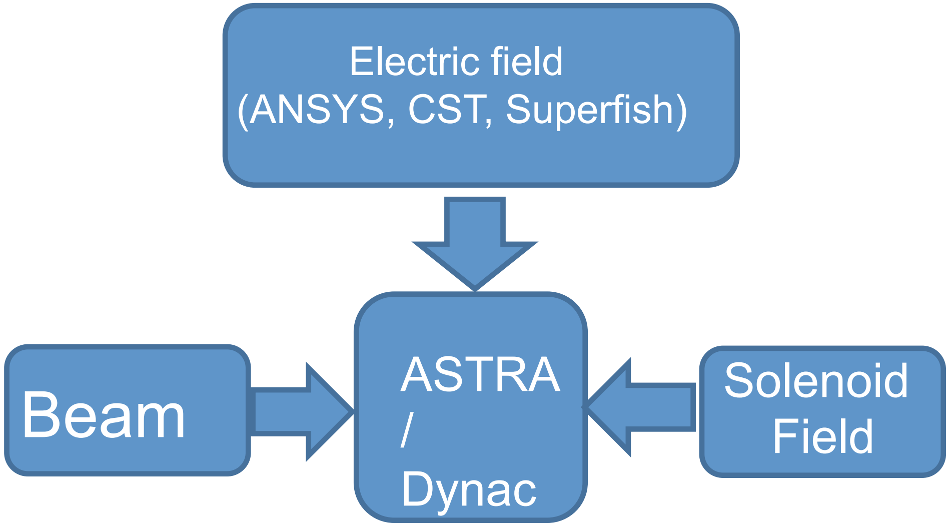
- Sensitive to contaminants
- Quick QE decay from 12% to 3% in 55 h
- Load-lock system for cathode transfer/ exchange
- **Evaporation CsBr on Cs_2Te improves the lifetime**



QE = f (t)	QE1 %	τ1 (h)	QE2 %	τ2 (h)
Transport carrier	3.85	18.9	9.17	3311
DC gun	2.24	65.9	12.74	779.5
RF gun	9.2	14	3.4	315

Simulation Methodology and Strategy



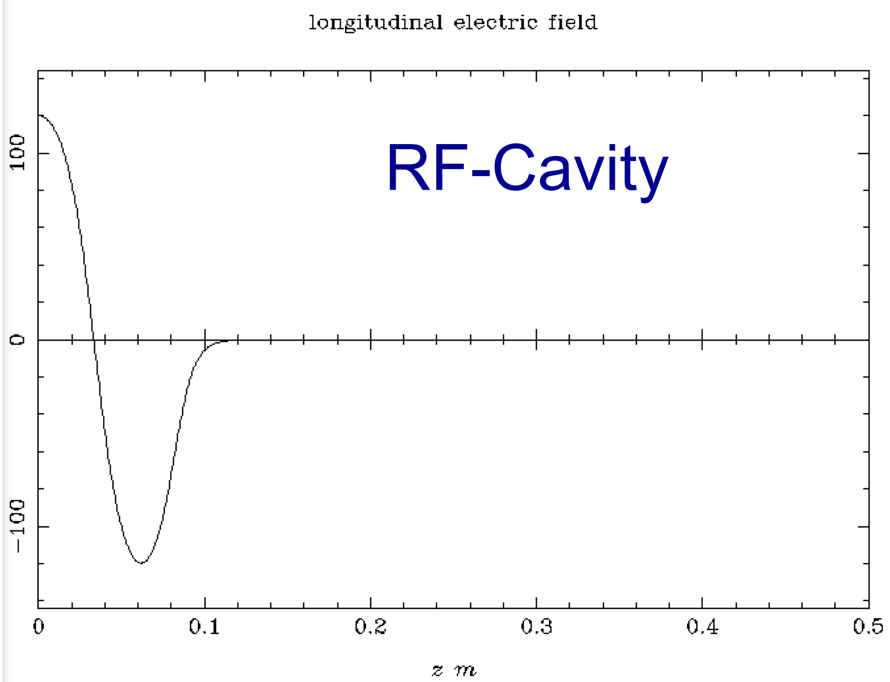


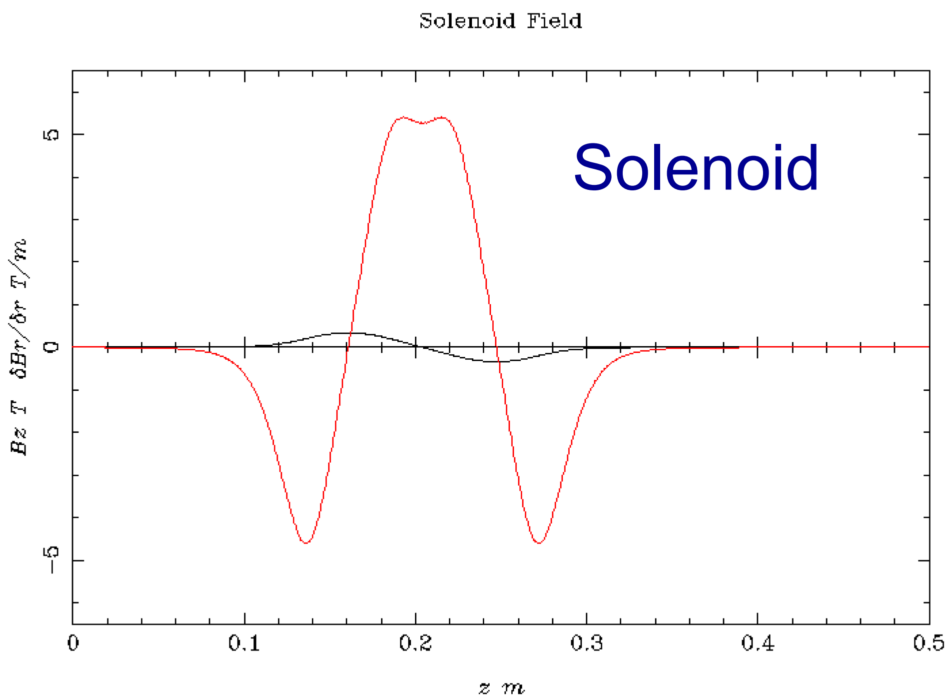
Material:
Beams: INFN Beam, SwissFEL Beam (Created from IASA/NTUA team)
Electric Fields: 1.5 Cell from INFN , SwissFEL 2.5 cell created with Matlab
Solenoids: INFN, SwissFEL look alike created with Matlab

All the possible combinations with respect to the Material have been investigated.

4 Scenarios with the lowest emittance are presented below

INFN -1.5 cell field and Solenoid

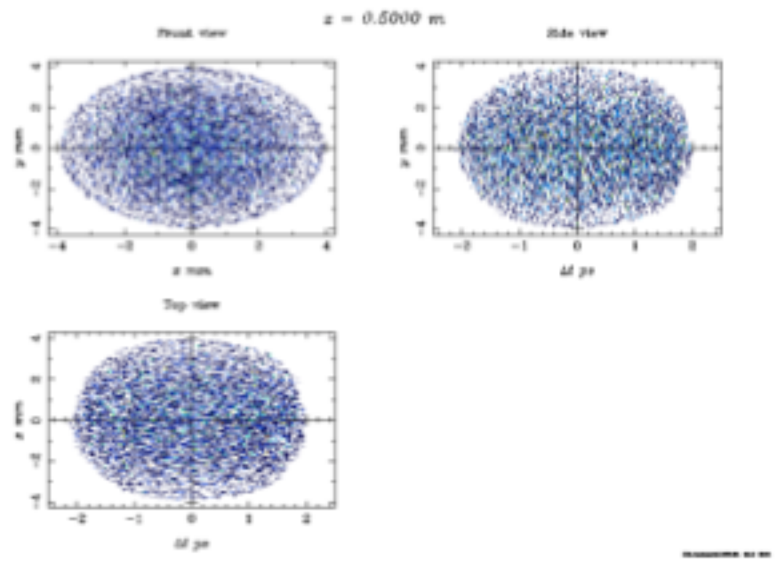




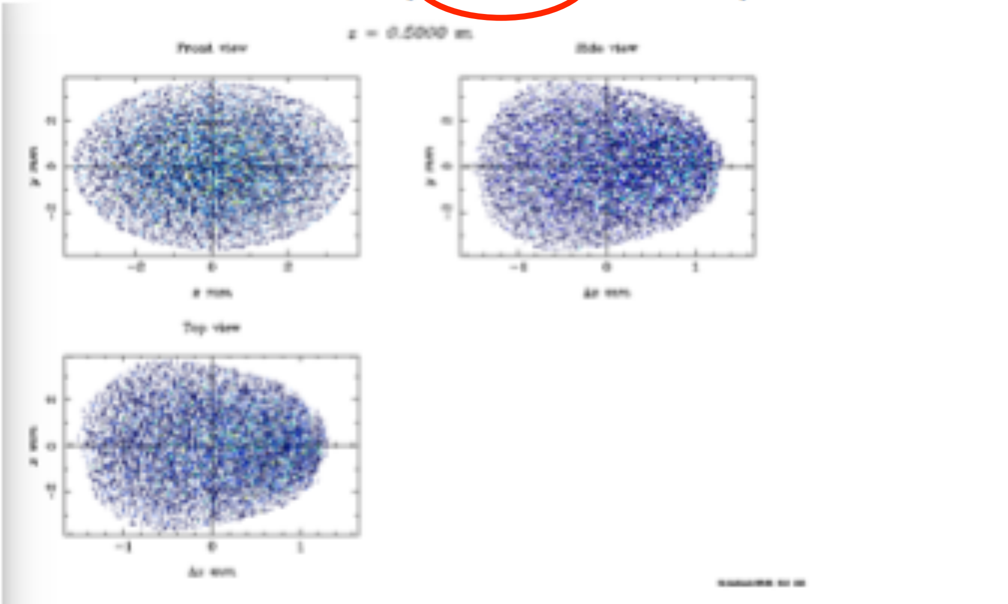

```
Cavity:

    Reading cavity field data from:      2015Gfield.dat
    Cavity Frequency               f =    2.856     GHz
    maximum gradient                      120.0     MV/m
    at                                    0.000     m
    estimated average gradient            27.29     MV/m
    nominal phase                         1.100     deg

--------------------------------------------------------------------------
Solenoid:

    Reading solenoid field data from:    ELI_SolGun_+-.poi
    maximum |Bz| field                    0.3380     T
    at                                    0.1608     m
    integral Bz squared                   9.6315E-03 T^2m
```

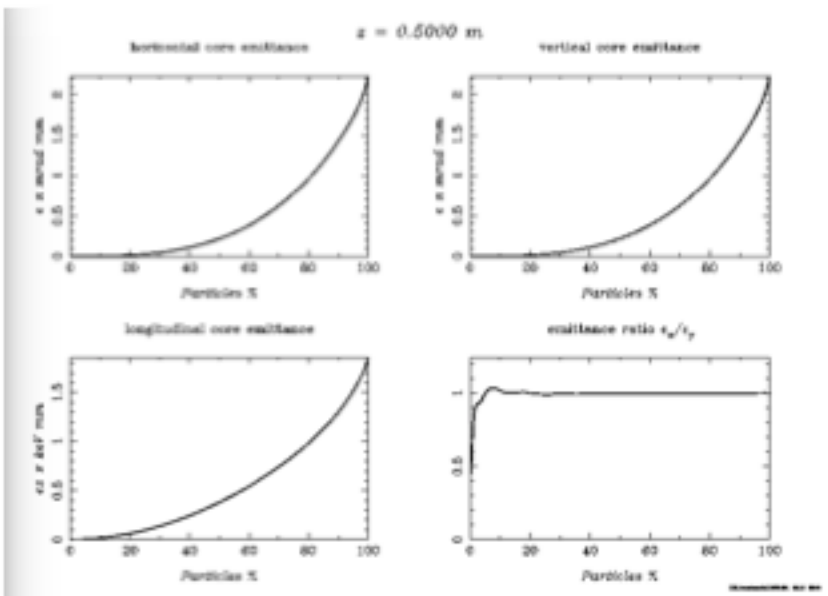
Preliminary Results

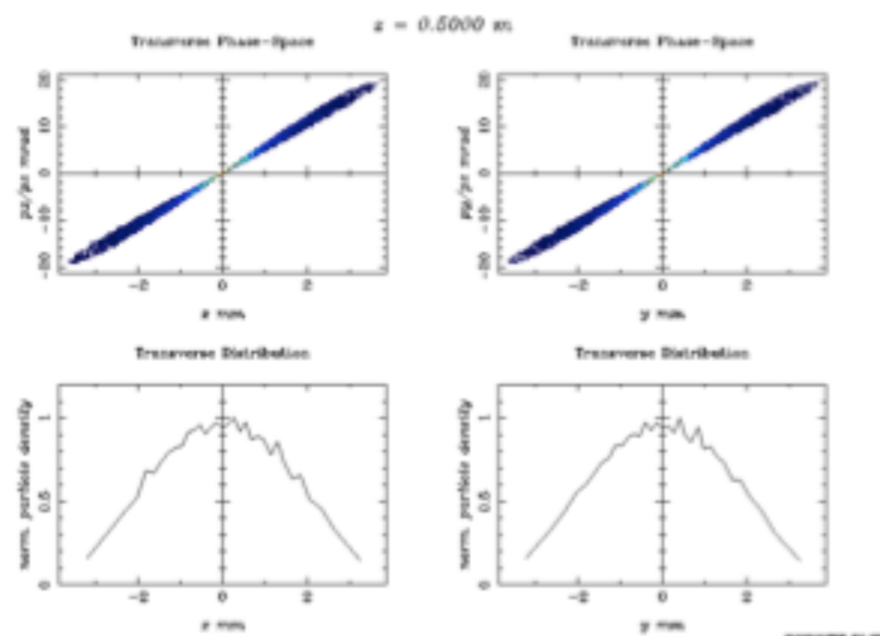
Scenario I : INFN Beam , 1.5 cell, INFN Solenoid



Scenario II:INFN BEAM, 2.5 Cell- SwissFEL , INFN solenoid

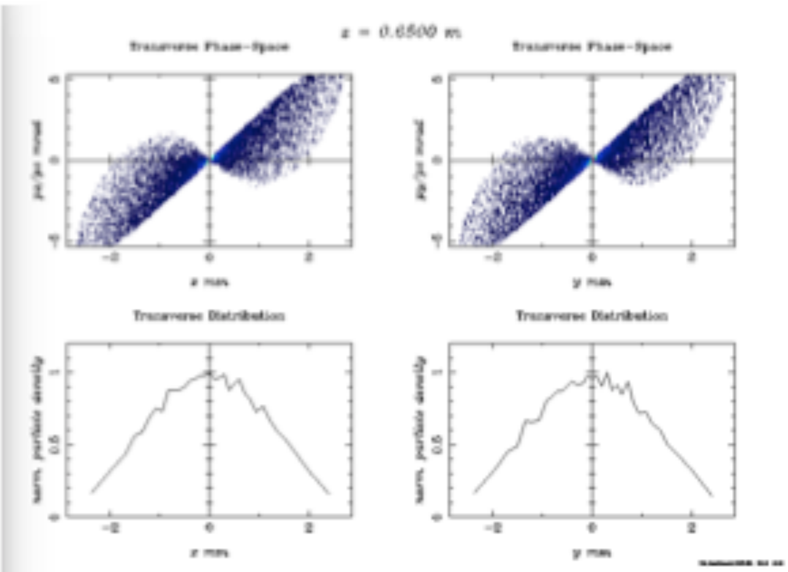


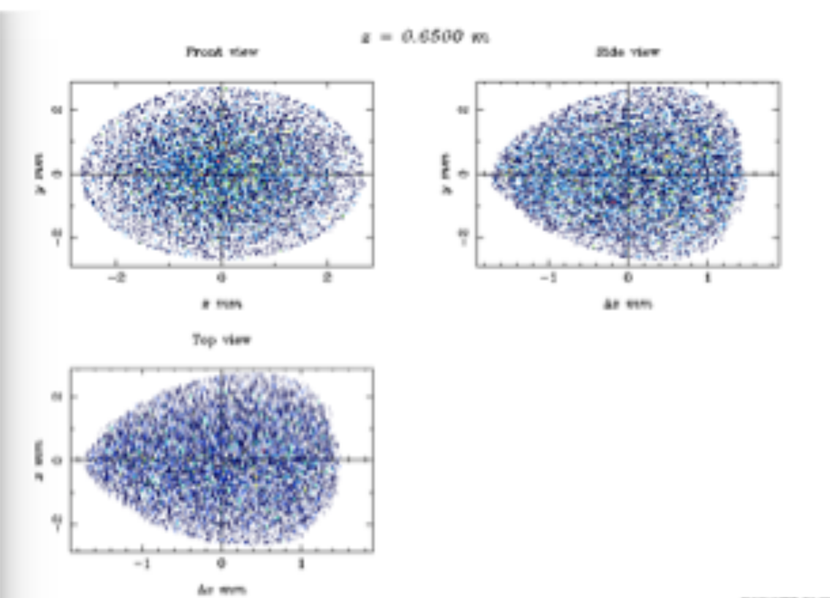




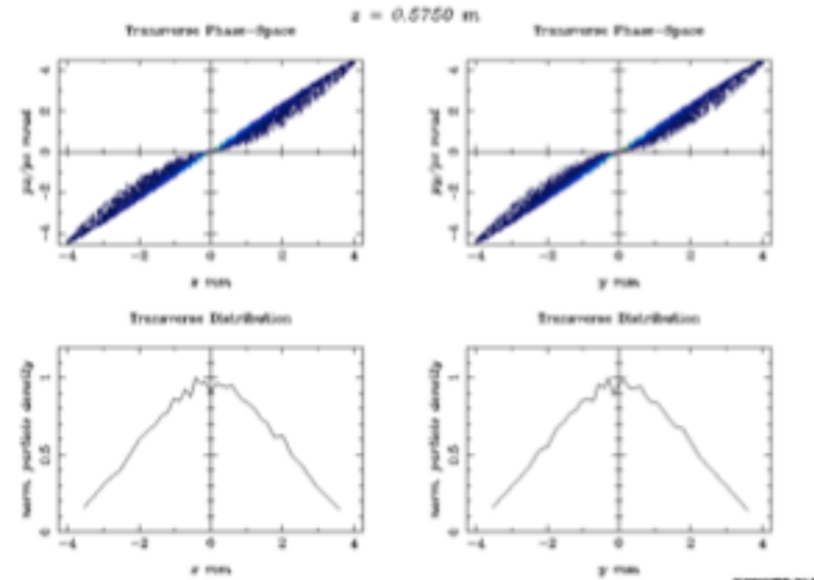
Preliminary Results

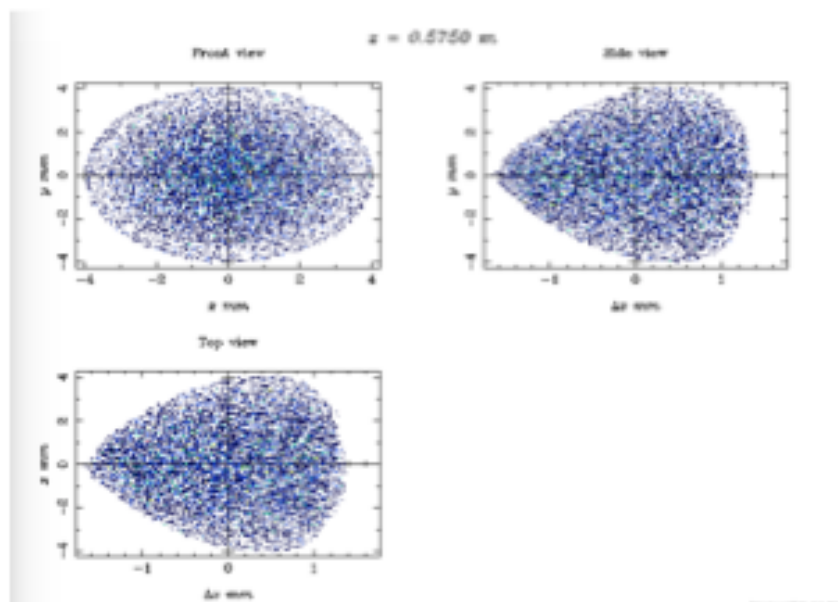
Scenario III: INFN Beam- 2.5 cell RF gun SwissFEL , created solenoid





Scenario IV- INFN Beam, 2.5 Cell RF gun SwissFEL
created solenoid shifted 0.1m





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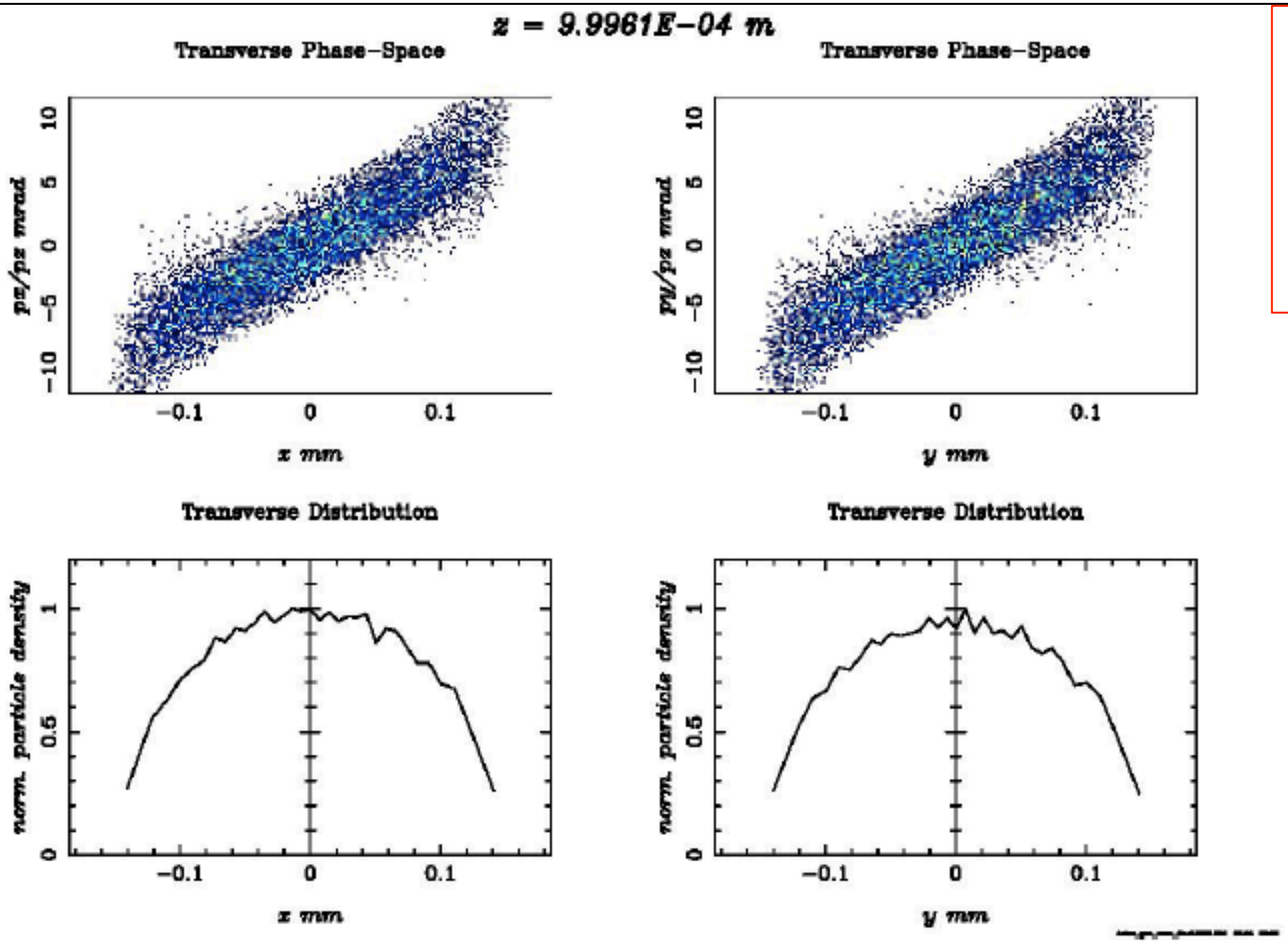
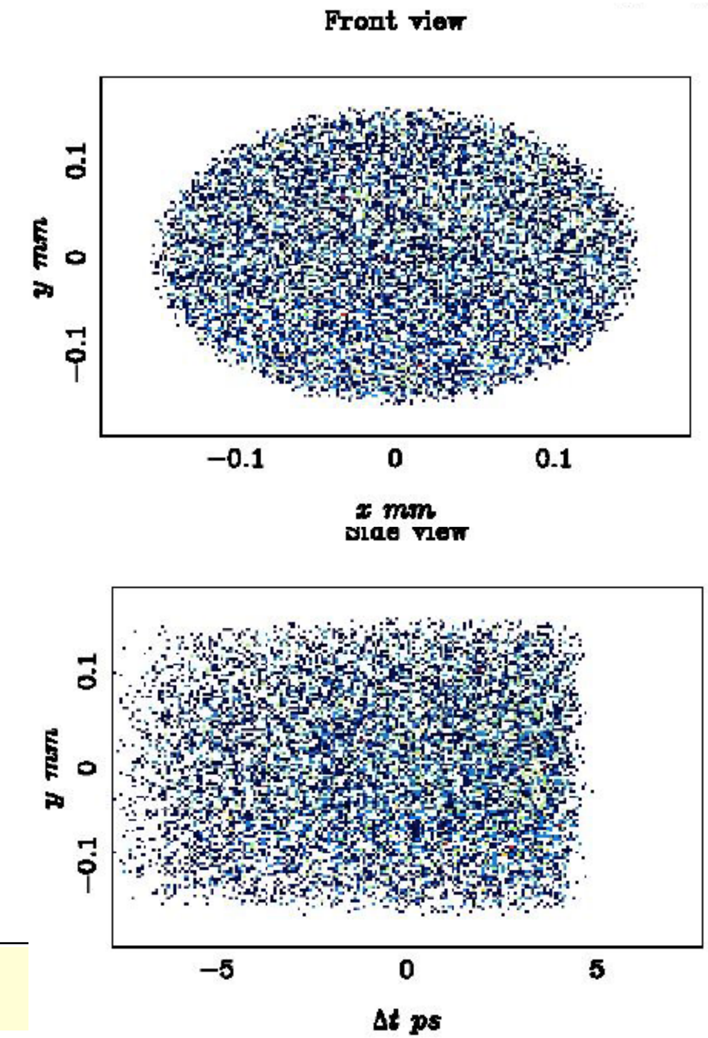
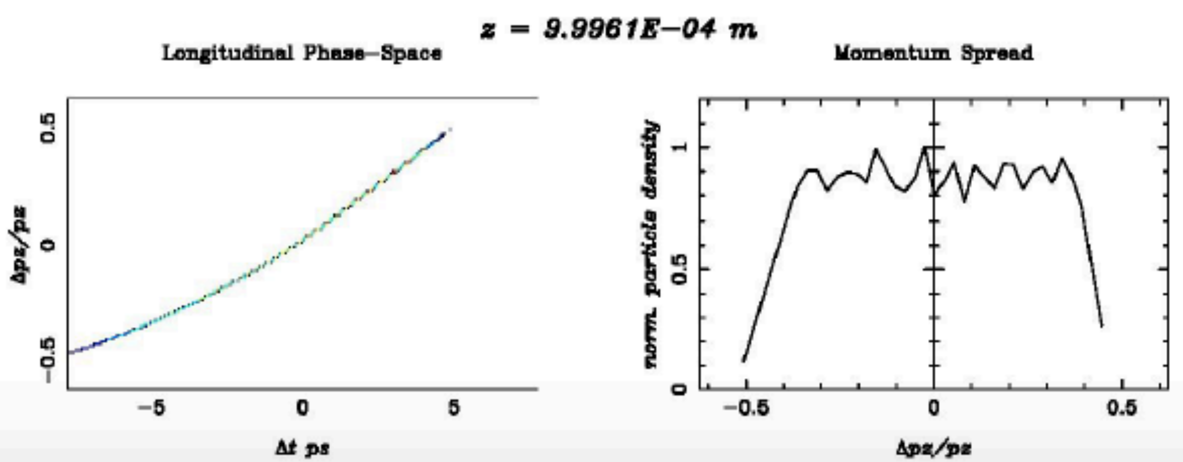
The Greek TEAM participation – IASA/NTUA



ASTRA code

1. the electron beam distribution very close to the cathode at z=0.002m
2. the electron beam density





Final Results

Laser spot size (mm)	0.08
Phase (degrees)	9.31
Solenoid field maximum (T)	0.1898
Solenoid position (m)	0.2939

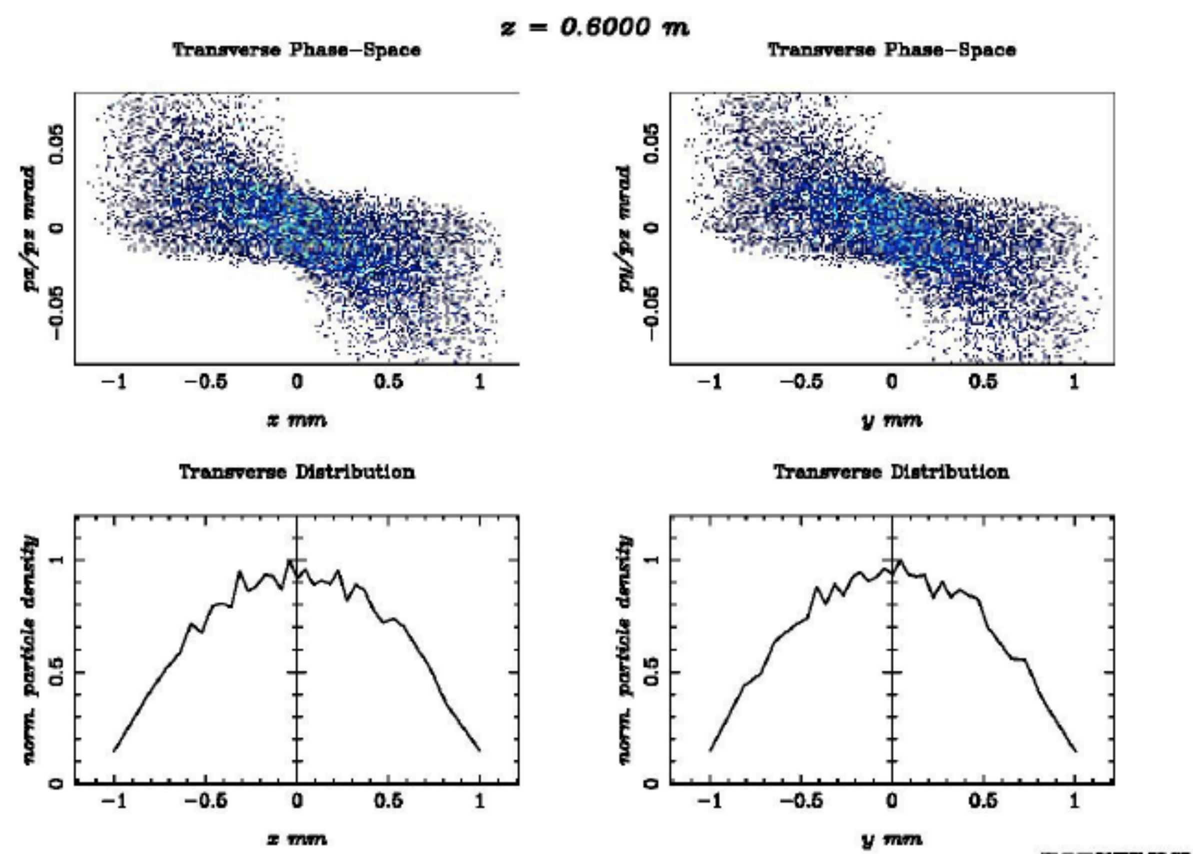


Figure A5: Transverse phase space

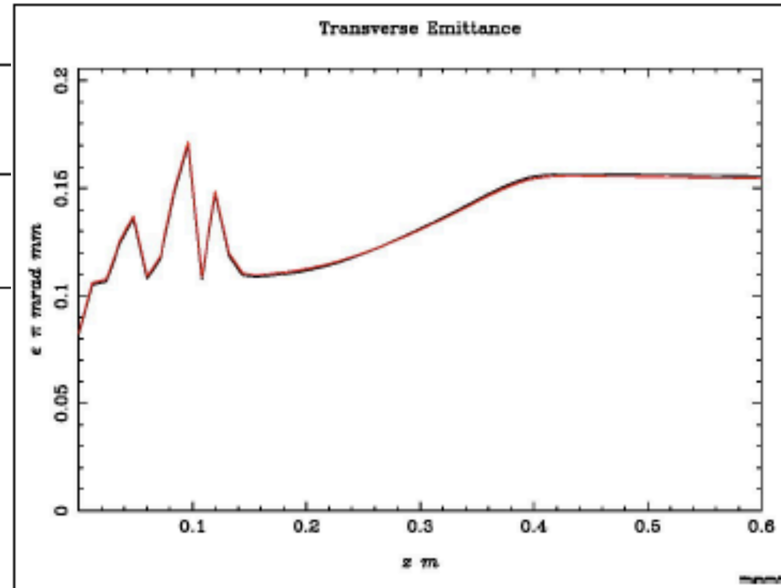
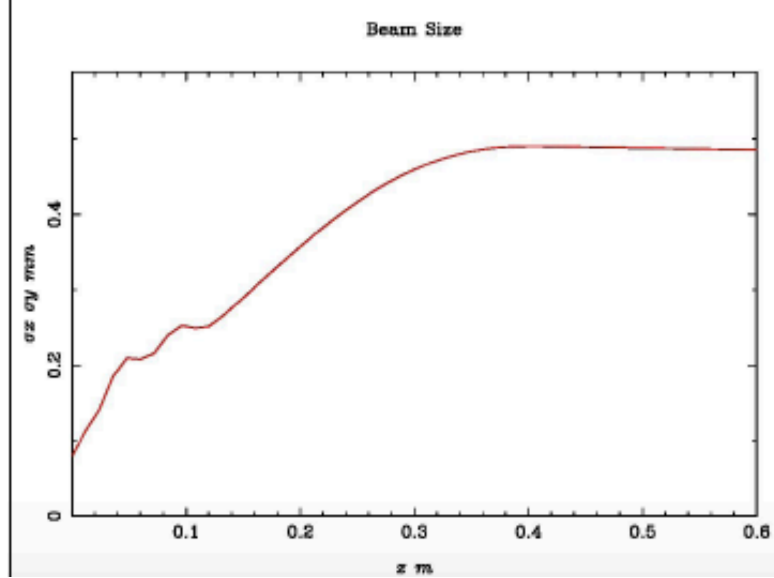
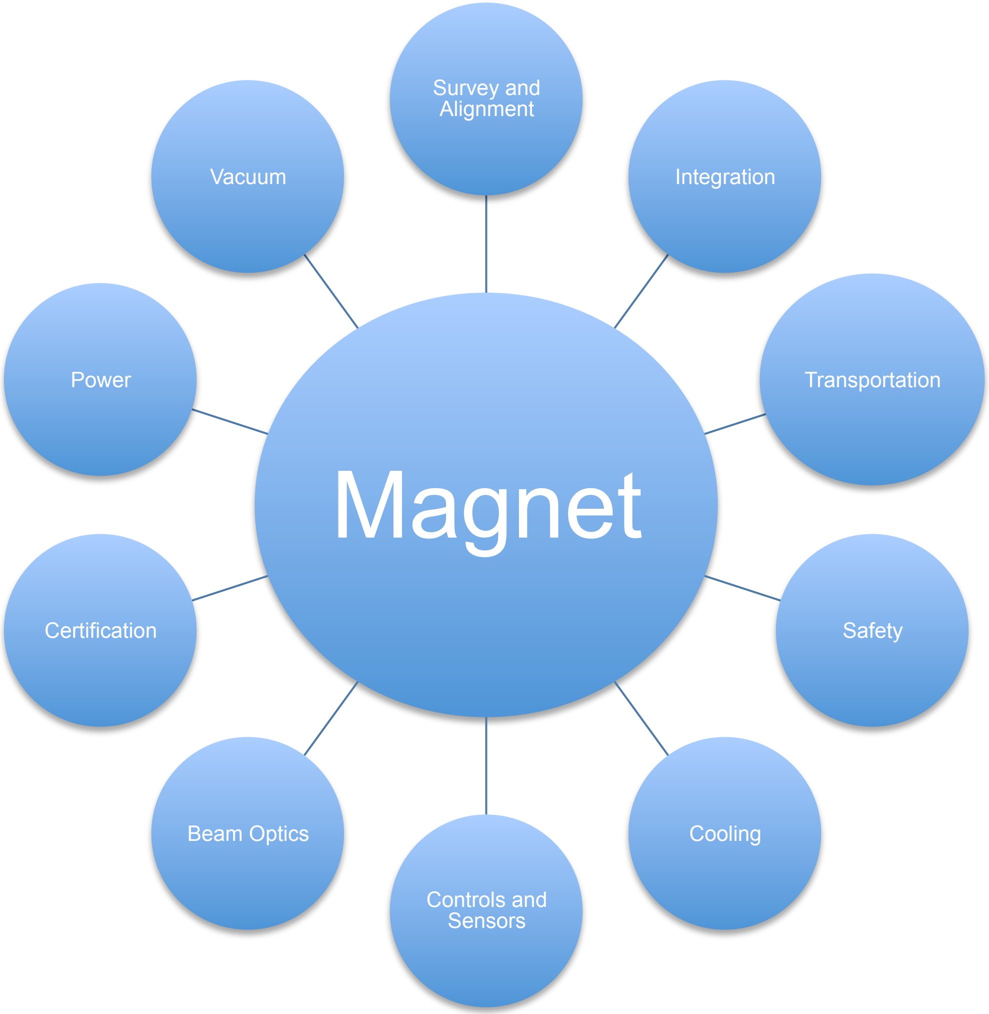


Figure A1 3: Transverse emittance



Methodology to mechanical & electrical design of the injector solenoid



- **Field Strength/Gradient**
- **Mechanical Length**
- **Integrated Field Strength/ Gradient**
- **Aperture and Good Field Region**
- **Field Quality (Field Homogeneity, Maximum allowed Multipoles- error and Tolerances, Time Constant)**
- **Operation Mode**
- **Supporting & transportation systems design**
- **General mechanical tolerances**
- **Electrical Parameters: Ampere Turns, Current**
- **Magnet Topology Bucking Coil, Steerer Coil**
- **Coil Design : Number of Coils and Cross Section, Material, Cross Section, Insulation Epoxy Impregnation,**
- **Cooling Circuit and Sensors, Hydraulic Connections, Integration to accelerator cooling system**
- **Temperature and Sensors**
- **Power Distribution : Power Supply, Cabling , Protection**
- **Integration of Sensors to Control System**
- **Alignment targets Adjustment tables Support jacks**
- **Magnetic measurement devices: Pick-up, hall probes**

Funded by the
European Union

The Greek TEAM participation - ESS

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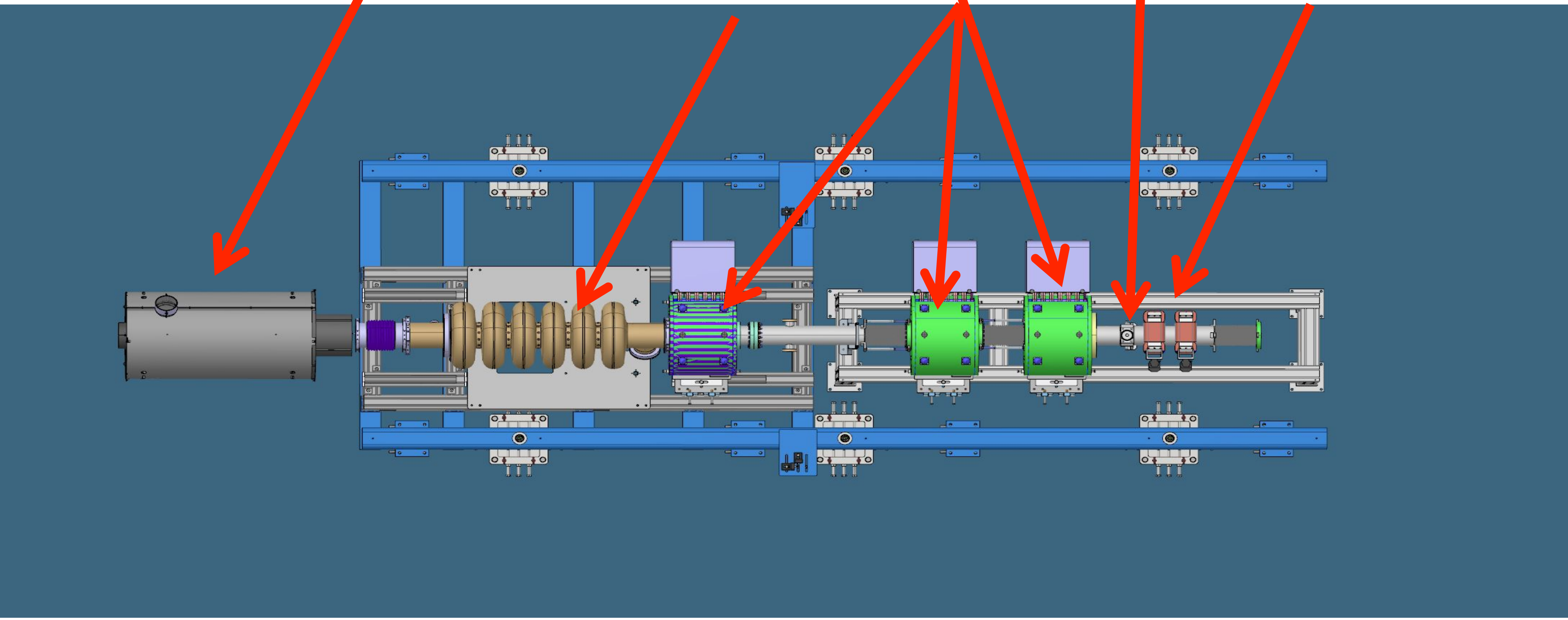
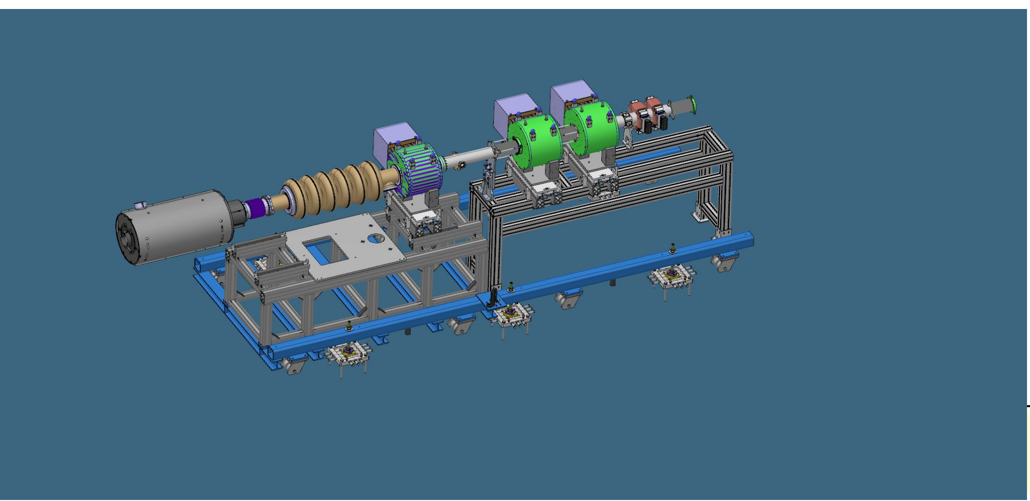
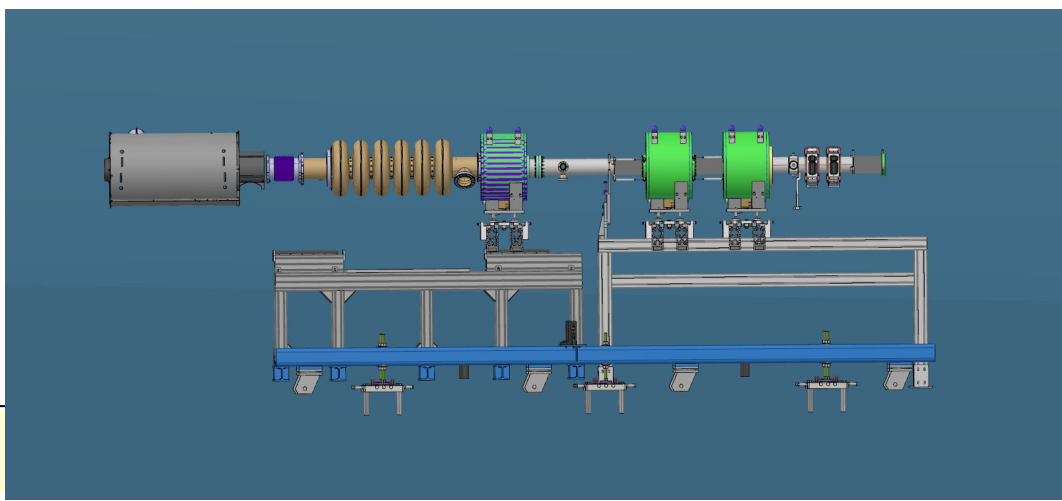
Photocathode/e-gun, RF-cavity, Solenoids, BPM, Steerers







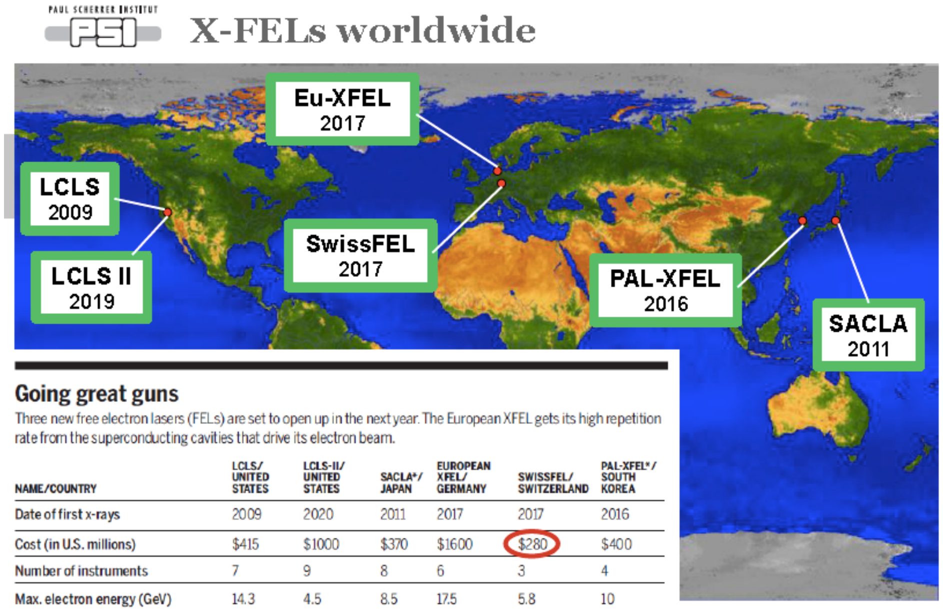
1. Data Management Plan

It is a formal document that outlines how data are to be handled both during a research project, and after the project is completed.

1st project deliverable by Greek Team: **D1.2: XLS Data Management Plan v1.0, 30 June 2018**

2. Cost & Risk Model Analysis

Sub-Systems	Rough Distribution %
RF-Gun	6
Injector	9
LINACS	16
Klystrons	25
Bunch Compressors	10
Magnets	5
Undulator	25
Controls & Operation	4



Going great guns

Three new free electron lasers (FELs) are set to open up in the next year. The European XFEL gets its high repetition rate from the superconducting cavities that drive its electron beam.

NAME/COUNTRY	LCLS/ UNITED STATES	LCLS-II/ UNITED STATES	SACLA*/ JAPAN	EUROPEAN XFEL/ GERMANY	SWISSFEL/ SWITZERLAND	PAL-XFEL*/ SOUTH KOREA
Date of first x-rays	2009	2020	2011	2017	2017	2016
Cost (in U.S. millions)	$415	$1000	$370	$1600	$280	$400
Number of instruments	7	9	8	6	3	4
Max. electron energy (GeV)	14.3	4.5	8.5	17.5	5.8	10
Min. pulse duration (femtoseconds)	15	15	10	5	2	30
Pulses per second	120	1,000,000	60	27,000	100	60

*SACLA is the Spring-8 Angstrom Compact free electron Laser and PAL-XFEL is the Pohang Accelerator Laboratory X-ray Free Electron Laser

3. Transfer Technology

Advanced Applications
Advanced XFEL Components
Intellectual Property

Funded by the European Union

Conclusions

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The Greek Teams:

- IASA/NTUA
- ESS/NTUA
- AUEB

Participate to one of the most innovative projects for designing the most effective 4th generation XFEL

It is very much important the Greek research community to get the proper knowledge and develop the Greek XFEL for many current applications in:

- Industry,
- Medicine,
- Energy, etc.

An XFEL facility may push the high tech start-up companies in their ambitious but reliable technological goals

Many Greek companies have expressed their intense interest to participate to the construction of XFEL(magnets, power supplies, elx.

Any institution willing to cooperate on that domain is welcomed!

The cooperation in the design and construction of an XFEL is necessary for the final success !!

Funded by the European Union

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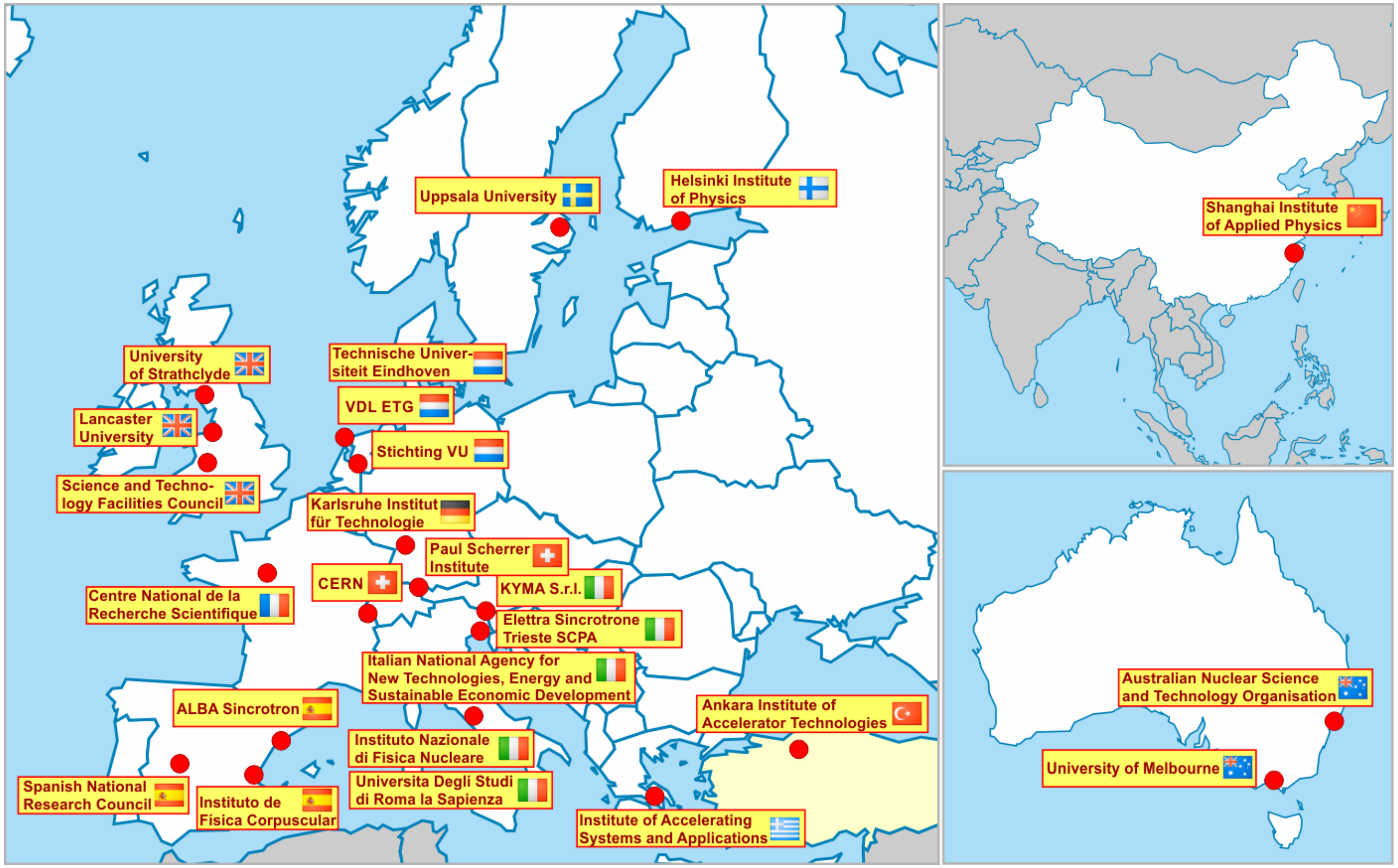
Thank you!

CompactLight@elettra.eu www.CompactLight.eu



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