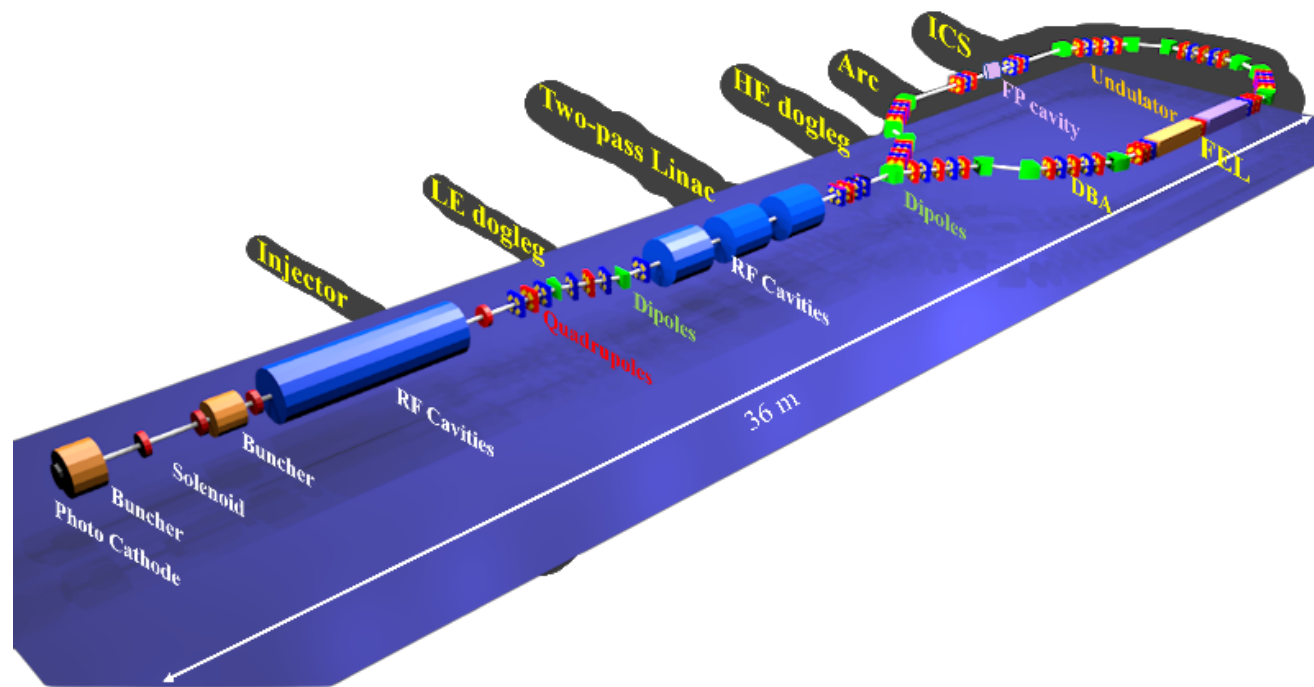




BriXSinO and Photocathode Development

D. Sertore
INFN Milano – LASA

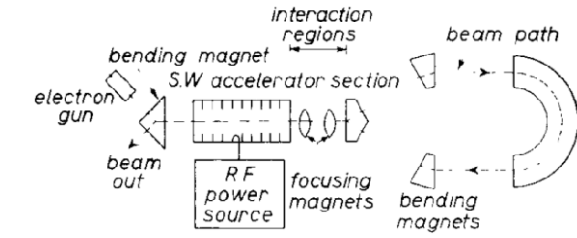
On Behalf of
Photocathode Group
HB²TF Group



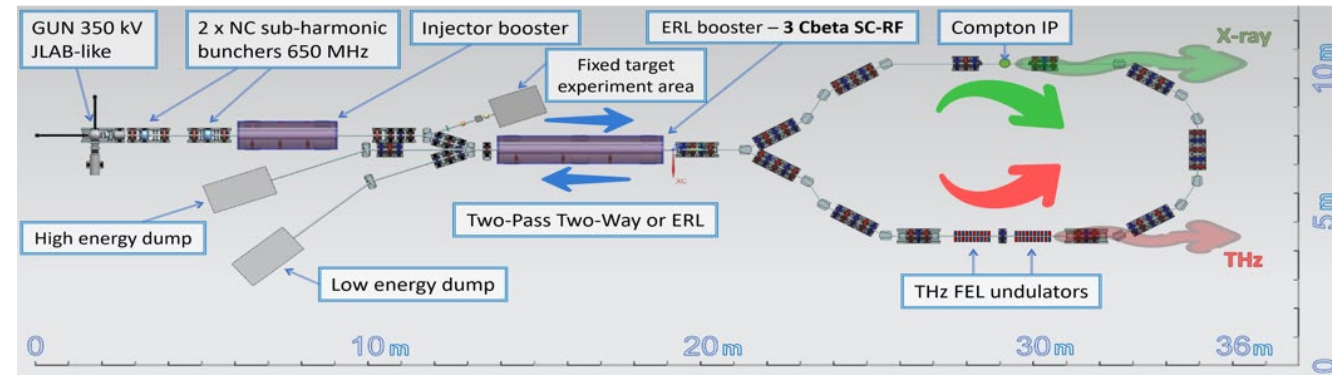
BriXSinO Project

Brilliant Source of **X**-Rays Based on **S**ustainable and **In**novative Accelerators

BriXSinO Principle of Operation



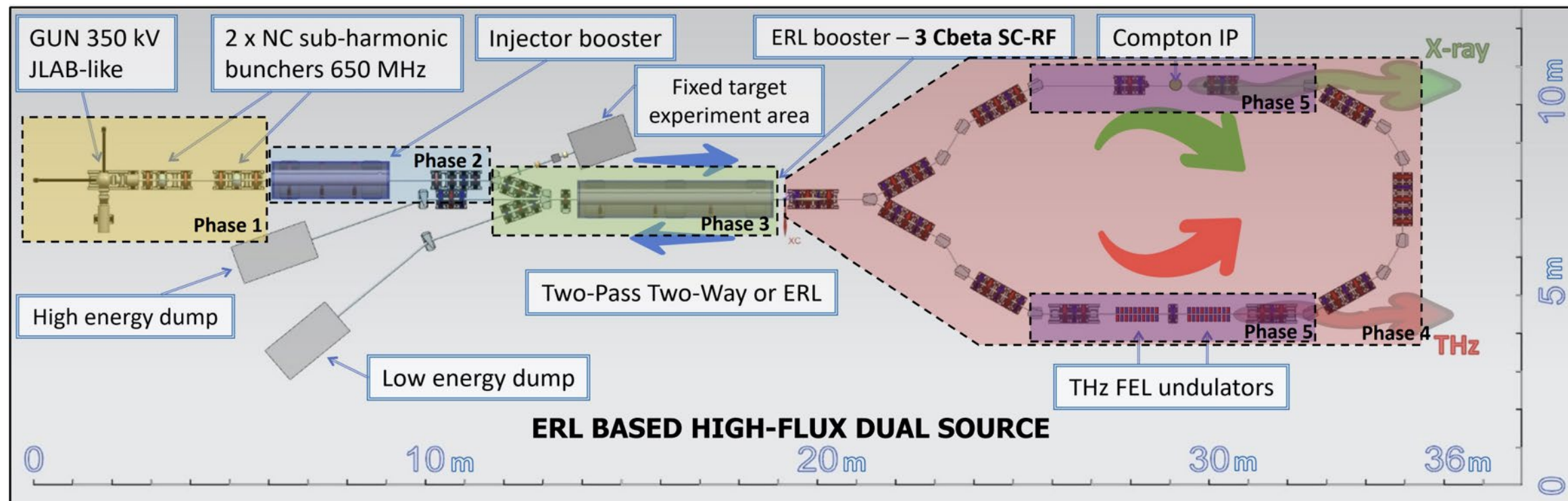
- A “**newly**” conceived scheme of ERL with **counter propagating beams** is proposed in BriXSinO.
- This **scheme allows:**
 - **ERL operation**
 - **Inverted Compton Scattering (ICS)**
 - **THz FEL**
 - **Two-pass operation:** the beam is reaccelerated when reinjected in the accelerating module (low current)
- **BriXSinO** will act as test facility for **fundamental questions of accelerator physics and strategies of Dynamics and Energetic** by hosting experiments for maximizing the energy sustainability and minimizing the AC power consumption.
- Moreover, **it will work as user facility by providing large quality coherent THz and X-Rays emission** from its high brightness accelerated electron beam, enabling important and advanced applications.



Parameter	two-pass acc.	ERL
Energy (MeV)	80	45
Bunch charge (pC)	100	100
Repetition rate (MHz)	0.9286	92.86
Average Current (mA)	$5 \cdot 10^{-3}$	5
Beam power @ dump (W)	$22.5 \cdot 10^3$	400
$e^-_{x,y}$ (mm-mrad)	< 1.6	< 1.6
Energy spread (%)	< 0.2	< 0.2

BriXSinO foreseen Schedule

BriXSinO evolution is based on **five Phases approach**; the completion of one phase leads to a discussion about the next phase.



Civil Engineering Status

PhASE2026



2025



2026

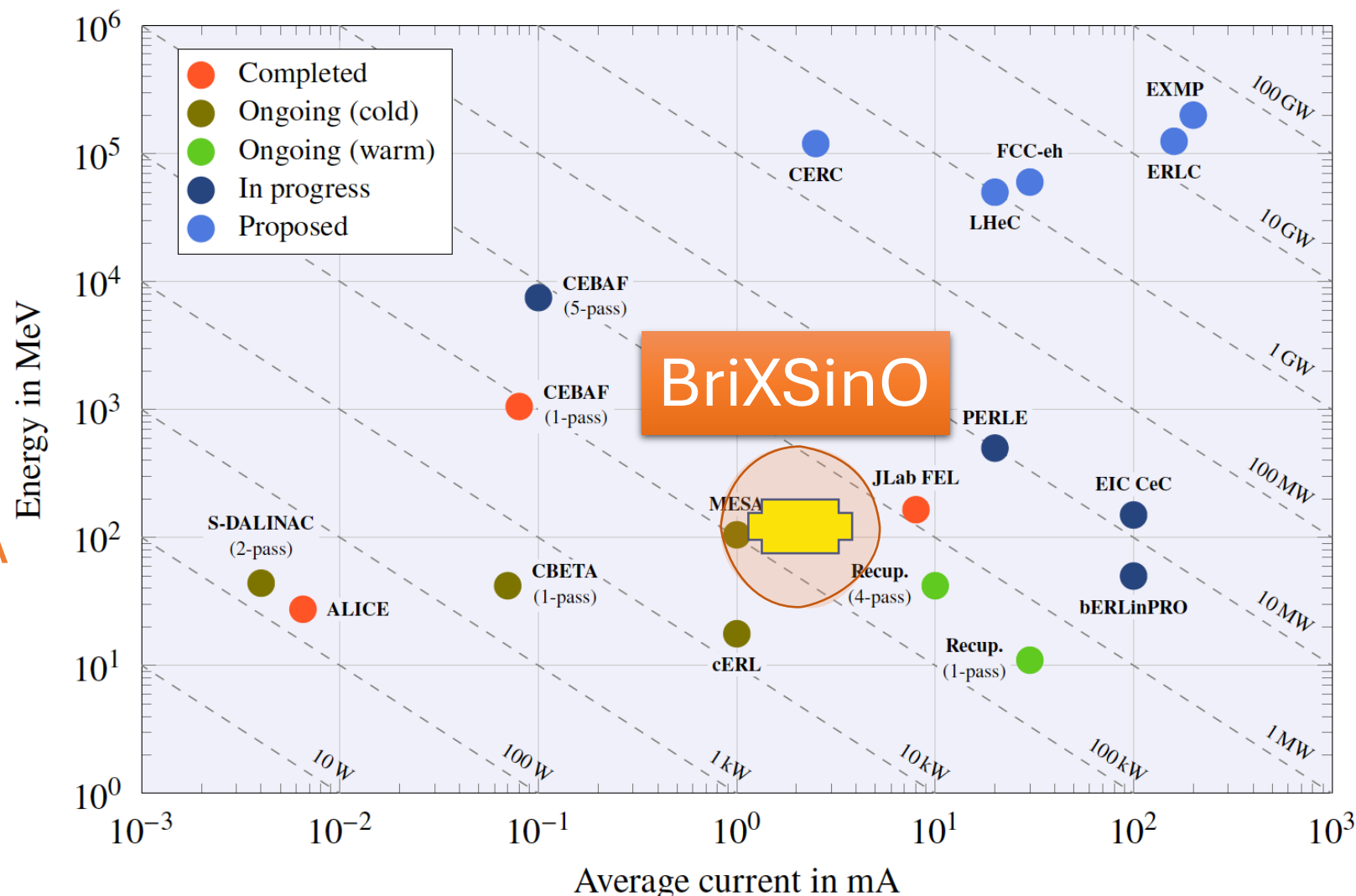
Overview of ERL Facilities



BriXSinO

45 MeV@5 mA

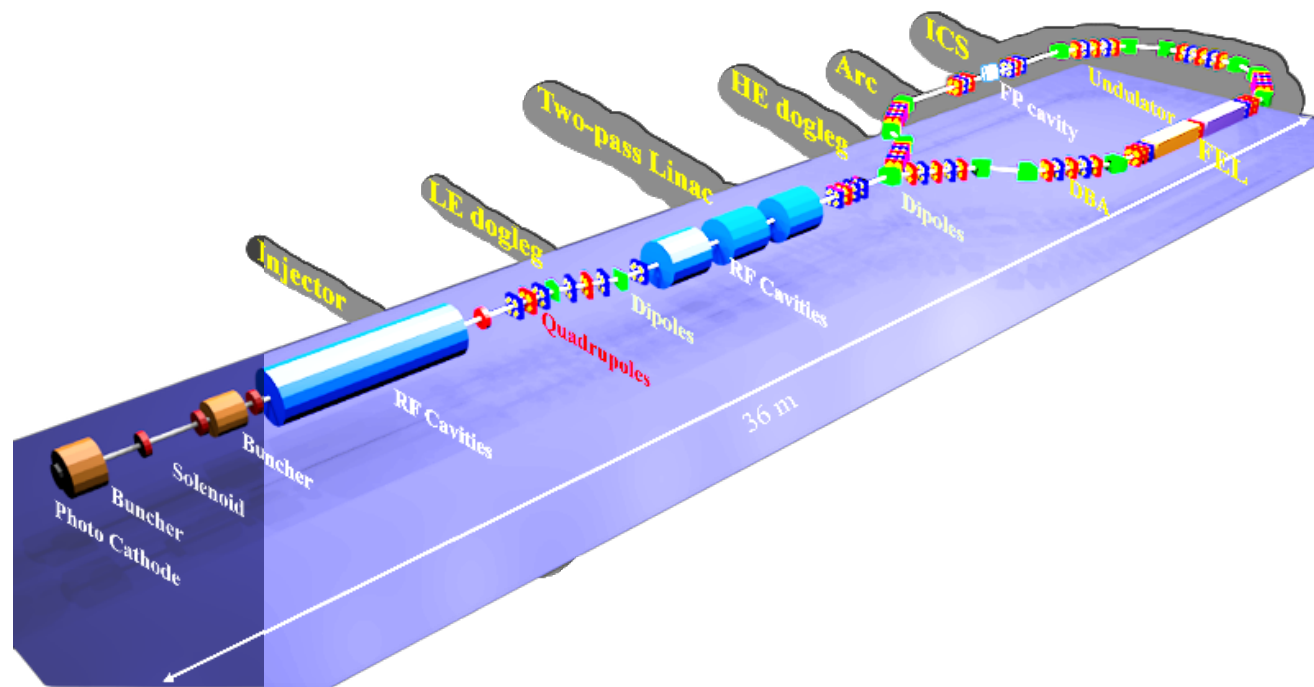
225 kW 50% efficiency



Costs



Technology



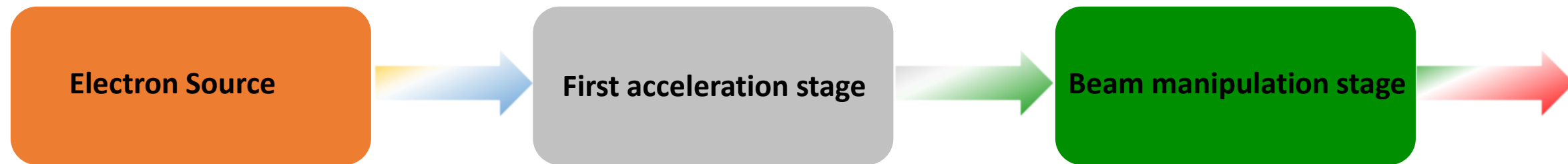
HB²TF : BriXSinO Phase One

High **B**rightness **B**eam **T**est **F**acility



HB²TF in a nutshell

- The HB²TF project aims to provide **a high power and high brightness CW beam**. The beam will provide different bunch charges at different repetition rate and energies.
- Moreover, BriXSinO **injector** might be **used for**:
 - **Fixed target experiments** performed with maximum electron energy of 10 MeV and 5 mA average current.
 - **Experiments of flash therapy** (total charge in a 200 ms time interval up to 1 mC)
 - **Bremsstrahlung photons with energy peaked at 7 - 8 MeV at an impressive flux of 10¹⁶ photons/s** (i.e. up to 30 kW X-Ray beam).
 - **Positronium generation** for fundamental studies of matter-antimatter asymmetry can be conducted at this test station.

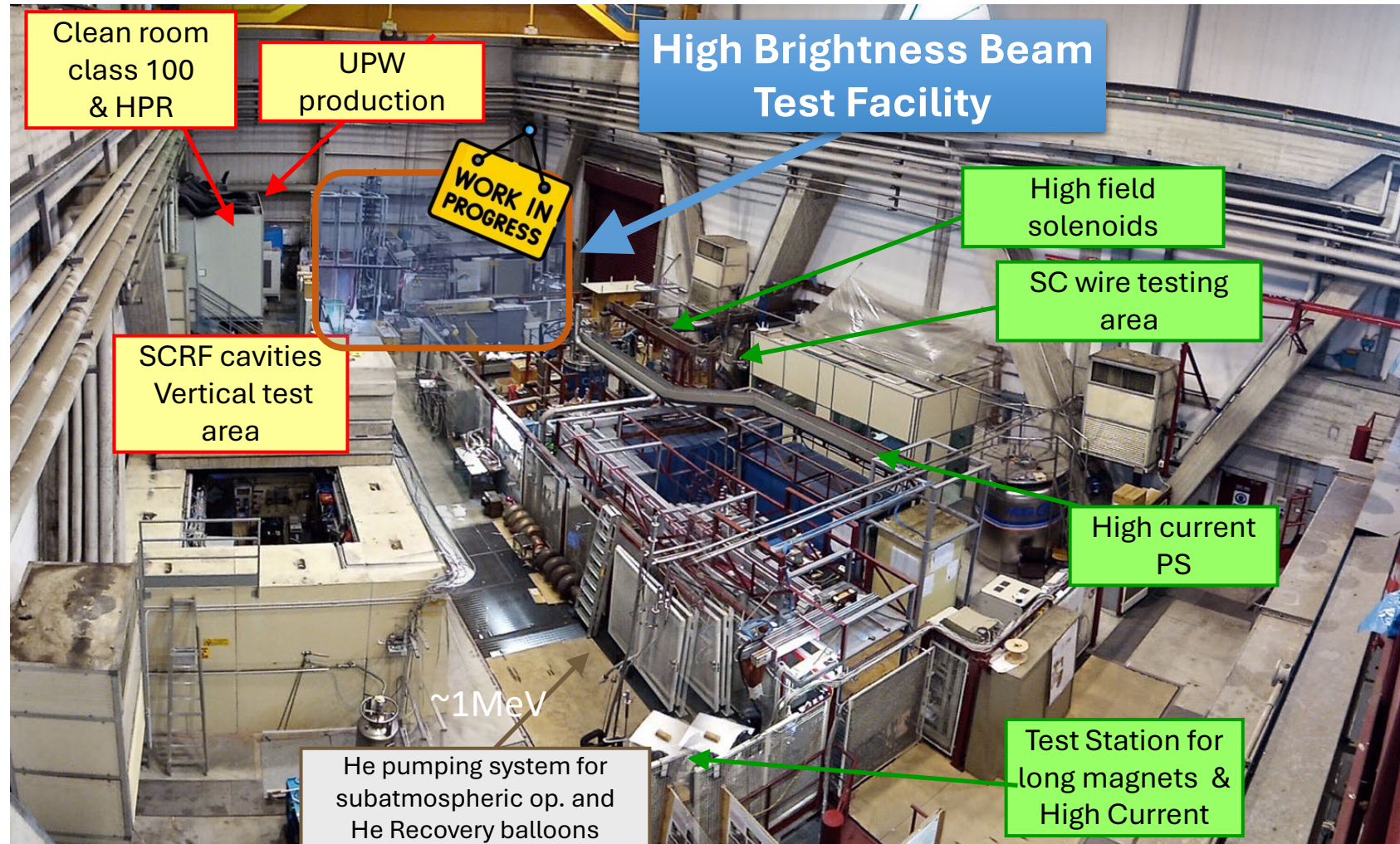


Photocathode

DC Gun

Bunchers and solenoids

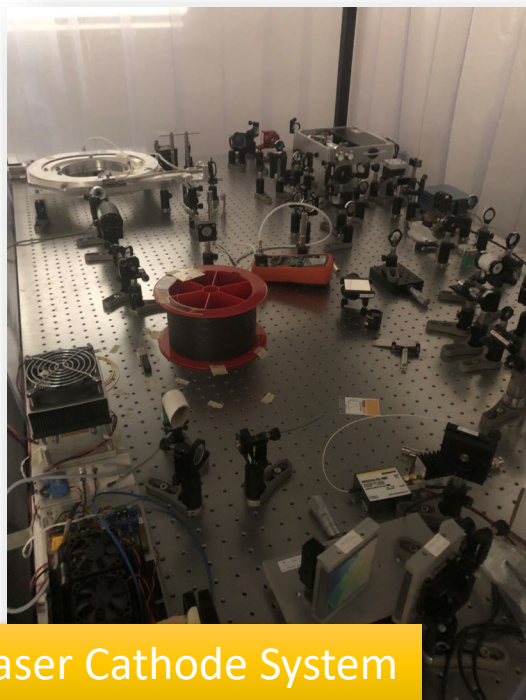
HB²TF at INFN LASA



HB²TF Assembly



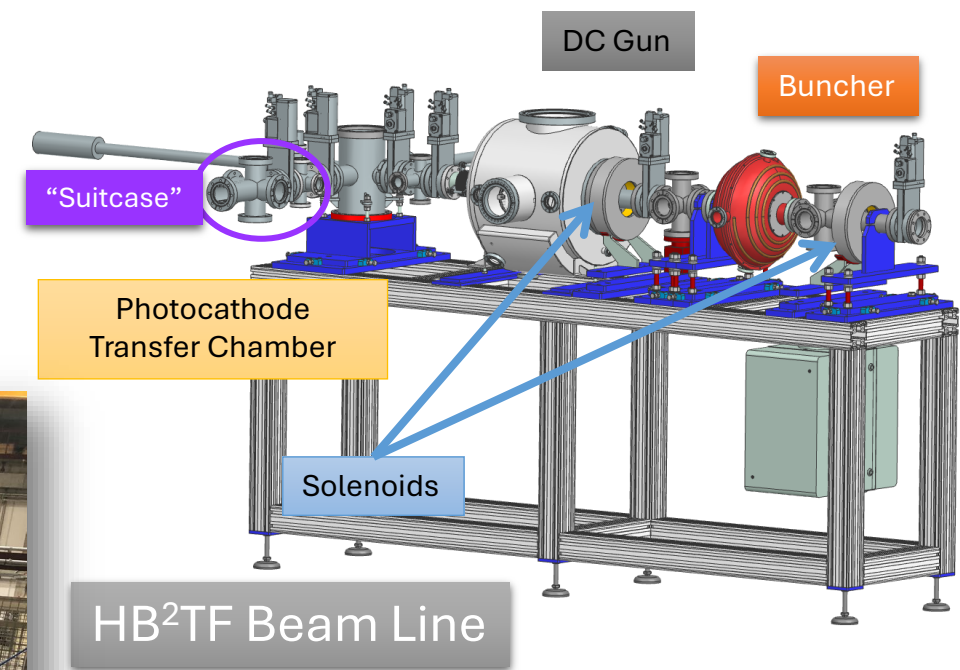
- The facility is on **daily evolution**
- All subsystems are **already installed** or under **final preparation** at vendor.
- **Laser** and **“INFN” photocathode handling system** installed and **ready to run**



Laser Cathode System



Photocathode Handling System

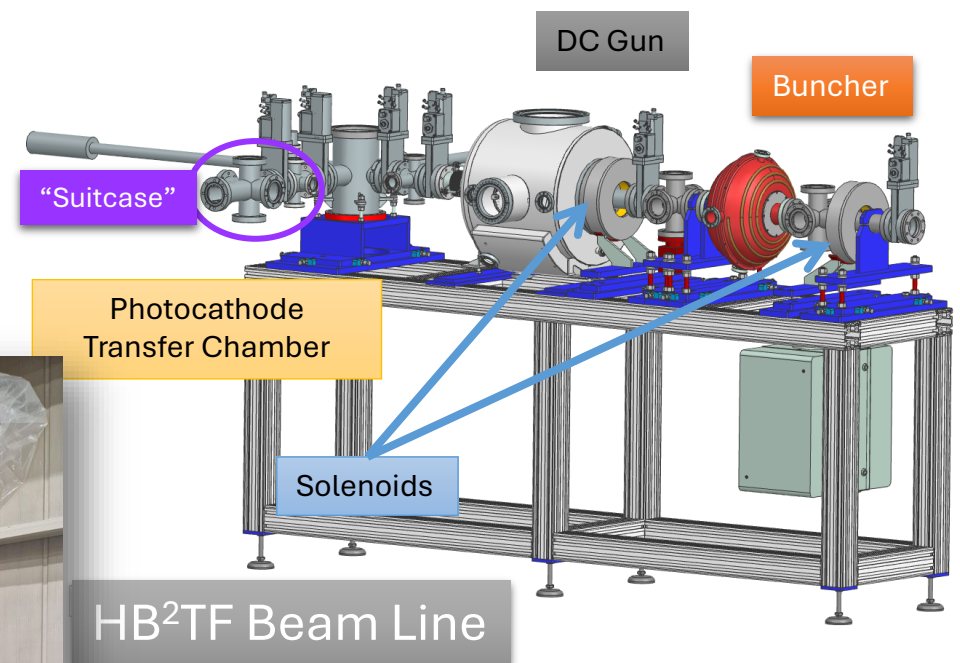
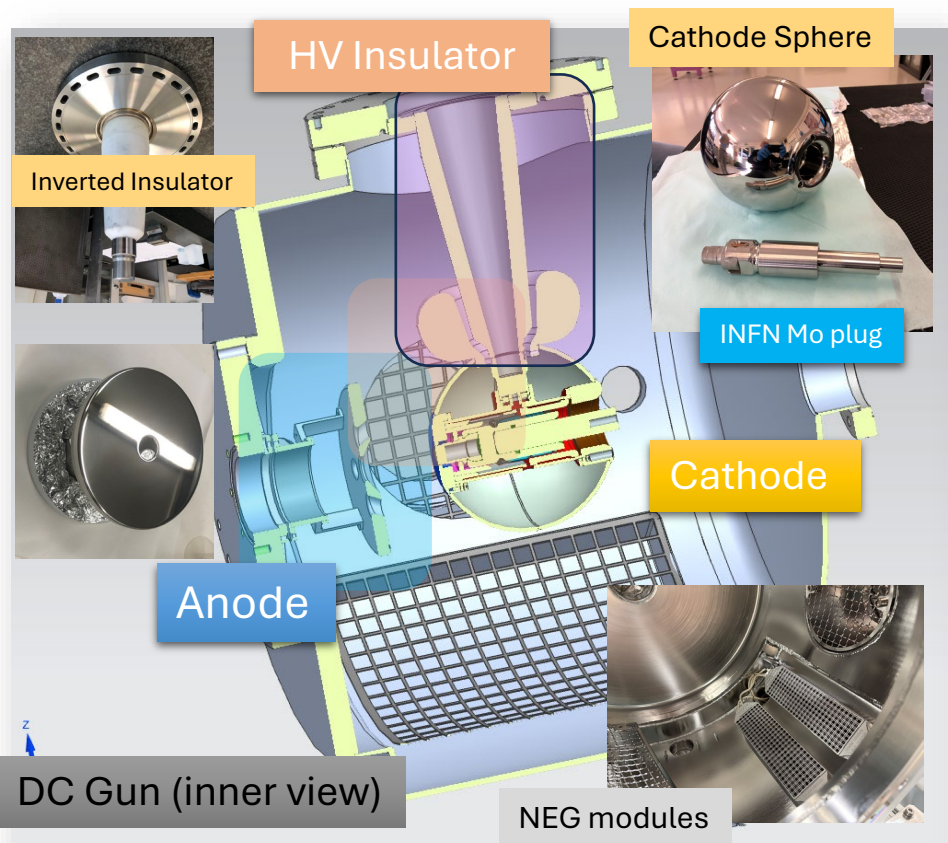


Laser Parameters	
Power	Up to 60 W
Wavelength	258.3 nm
Pulse Length	440 ps
Rep rate	Up to 100 MHz

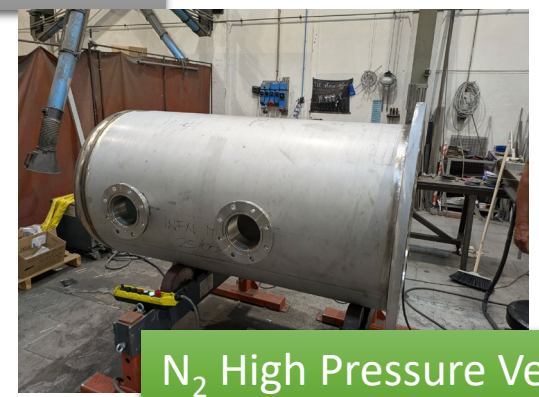
HB²TF Assembly



- **DC Gun**, based on “inverted” insulator, and **HV system** are **under assembly**

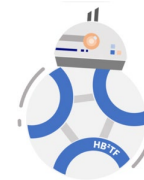


HV PS @ LASA
-450 kV – 3 mA



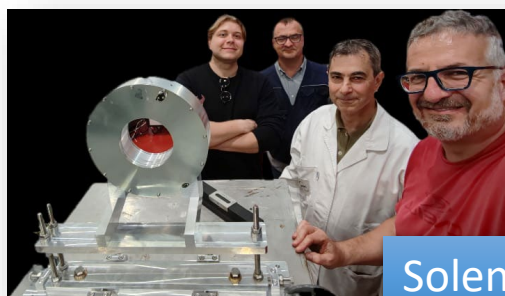
N₂ High Pressure Vessel

HB²TF Assembly

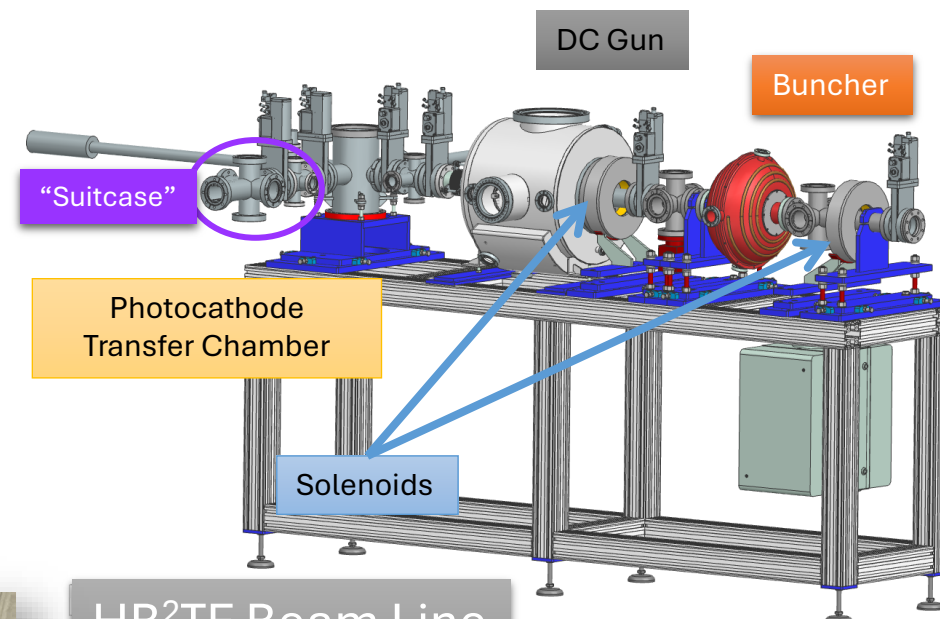


- **Solenoids** measured, **buncher** in fabrication, **beam line** under assembling.
- **All service systems, RF and LLRF are being installed**

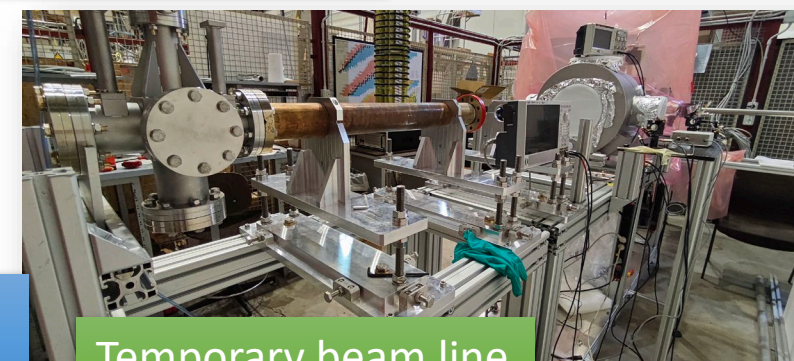
Buncher two halves after machining



Solenoid



HB²TF Beam Line



Temporary beam line and diagnostic cross



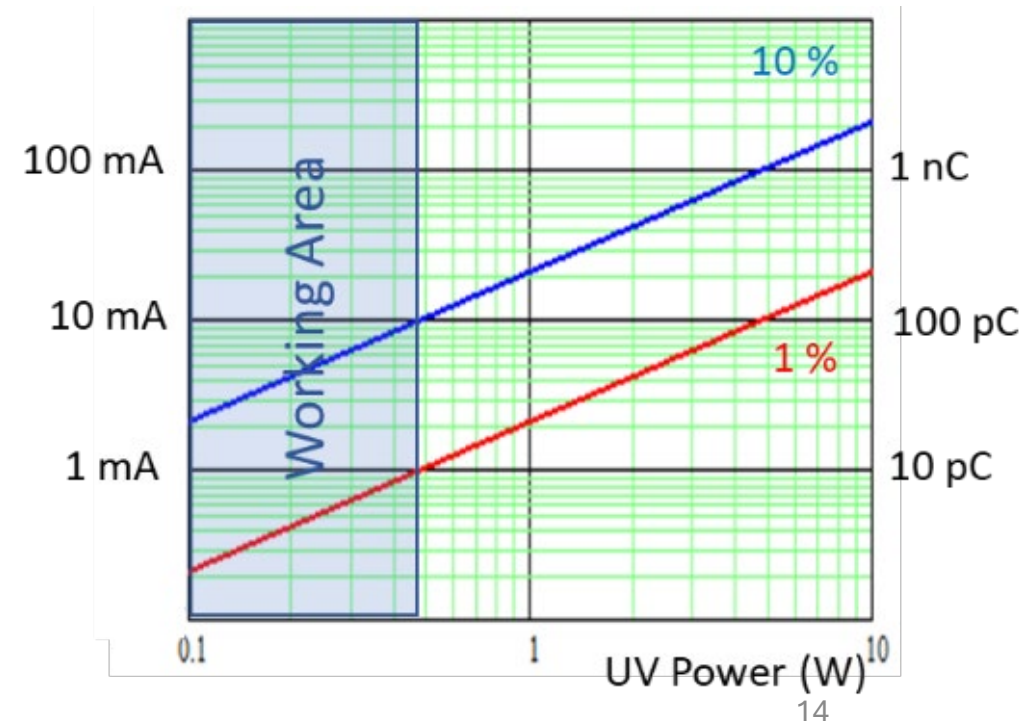
Chiller, RF Switch and RF Load (20 kW)

	Buncher 1	Buncher 2
f_0 (π -mode) [MHz]	650	
β (v/c)	0.74	0.906
Input energy [MeV]	0.3	0.638
E-field ampl. [MV/m]	2.7	
Active length [m]	0.171	0.209
Quality factor Q_0	$3.2 \cdot 10^4$	$3.67 \cdot 10^4$
Ext. quality factor Q_{ext}	$3.02 \cdot 10^4$	$3.24 \cdot 10^4$
R/Q [Ω]	195.7	223
Geometry factor G [Ω]	211	244
E_{pk}/E_{acc}	3.07	3.88
B_{peak}/E_{acc} [mT/(MV/m)]	2.94	3.73

Photocathode Development

Photocathodes for HB²TF

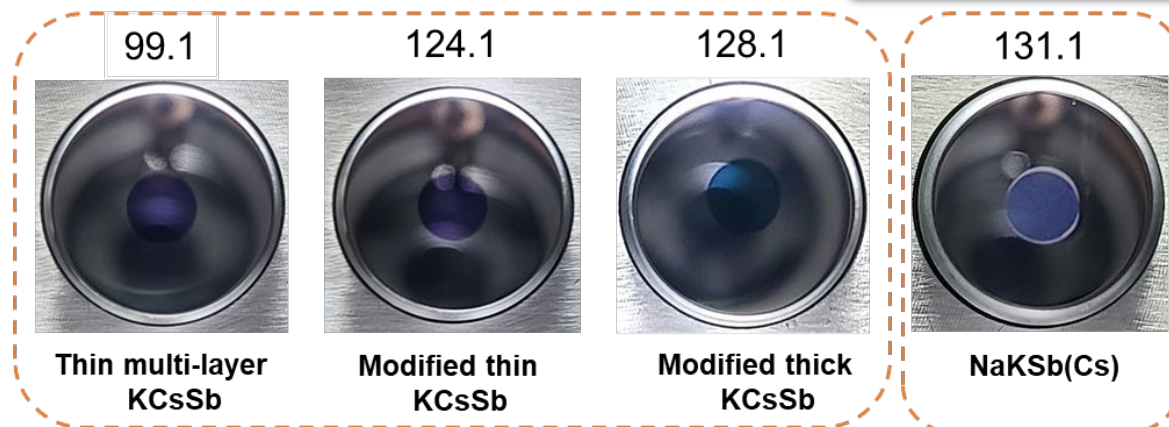
- For HB²TF **Cs₂Te photocathodes** will be used as electron sources
 - Average QE at the production $\geq 10\%$ in UV range, in operation typically used until QE 0.5%
 - Vacuum quality: low 10^{-10} mbar (in the production stage), low 10^{-9} mbar (in operation mode)
- Laser system (**Yb laser**, $\lambda_{\text{fund}} = 1035$ nm, $P = 10$ W, rep. rate $1 \div 93$ MHz, 190 fs):
 - UV is needed** for the photocathode operation:
 $\lambda^{4\text{th}} = 258.75$ nm, $P = 0.5$ W
- Photocathode requirements** in operation:
 - Q: **up to 50 pC**; I_{ave} up to 5 mA
 - Lifetime**: as long as possible
 - On-line measurement**: QE and reflectivity characterization
 - Post-usage analysis: after operation, photocathodes will be analyzed in the production system



Sb based photocathodes

- **100 MHz operation** for **5 mA** beam has stimulated the investigation **alkali antimonide** photocathodes. These studies have been initiated in **collaboration** with **DESY PITZ** to investigate the operation of these photocathodes in RF gun.
- **Different materials** and **thickness** have been investigated. **NaKSb(Cs)** has emerged as a possible candidate due to its robustness

Second Batch at PITZ



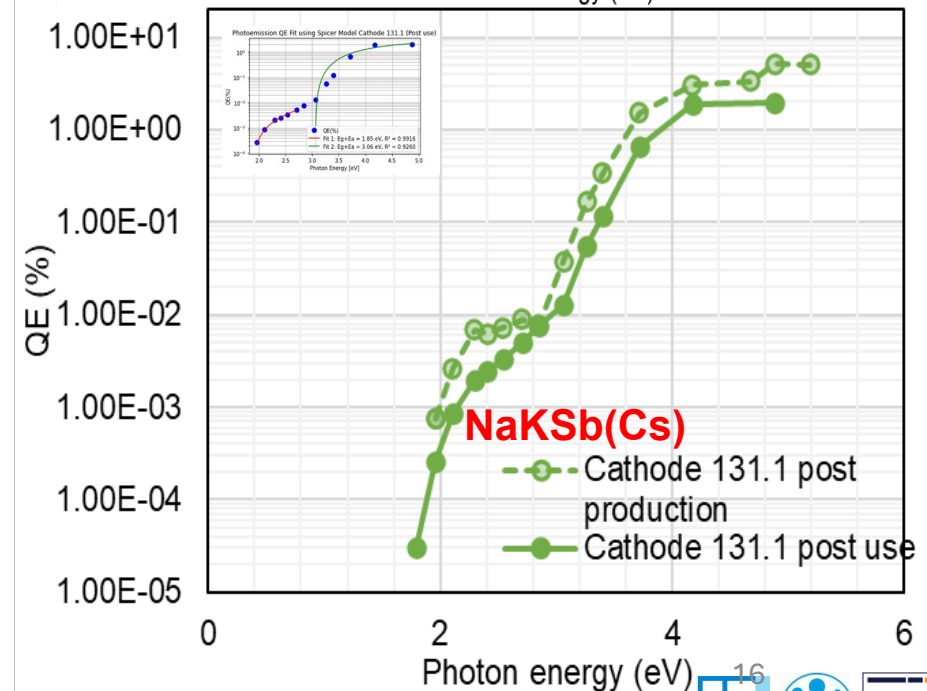
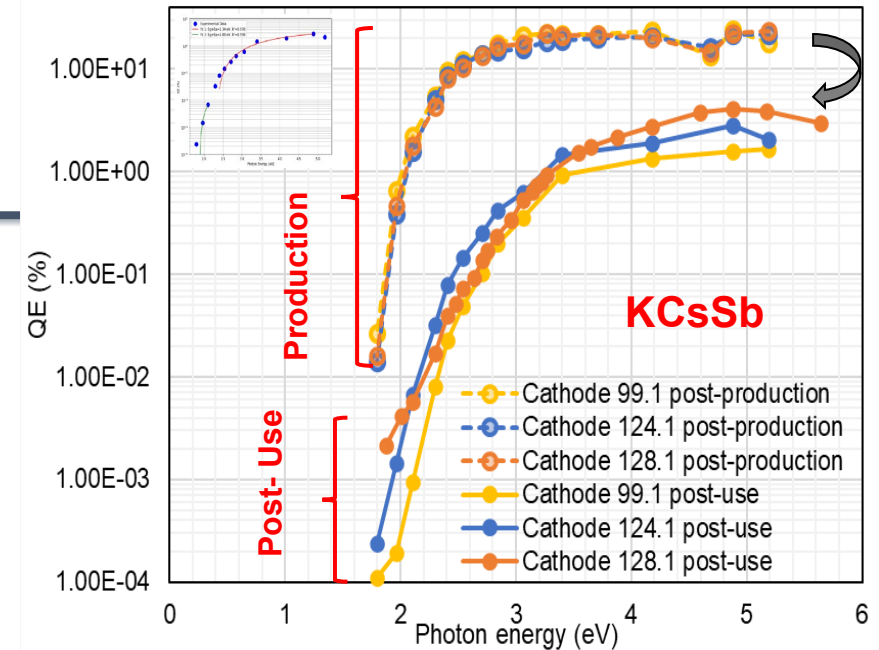
- **3 KCsSb** cathodes (modified recipes):
 - 1 **thin multi-layer “yo-yo”** cathode (cathode 99.1)
 - 1 **modified thin** cathode* (cathode 124.1, Sb = 5 nm)
 - 1 **modified thick** cathode* (cathode 128.1, Sb = 10 nm)
- 1 **NaKSb(Cs)** cathode (*cathode 131.1*)

Spectral Response

- **Spectral response + reflectivity** measured for all four cathodes.
- **KCsSb cathodes: QE decreased** at all wavelengths.
- **NaKSb(Cs) cathodes: No significant QE change** was noticed.
- **Eg+Ea: No significant change** observed in any of these four cathodes.

Cathode	Post use Eg+Ea
All 3 KCsSb cathodes	Fit1: 2.34 eV Fit2: 1.9 eV
NaKSb(Cs)	Fit1: 1.85 eV Fit 2: 3.06 eV

- Spectral reflectivity **behavior** is similar between **fresh** and **used** cathodes.
- **No significant change** in the spectral **reflectivity peaks** indicates the fundamental **arrangement** of **energy bands** is largely intact in the bulk.



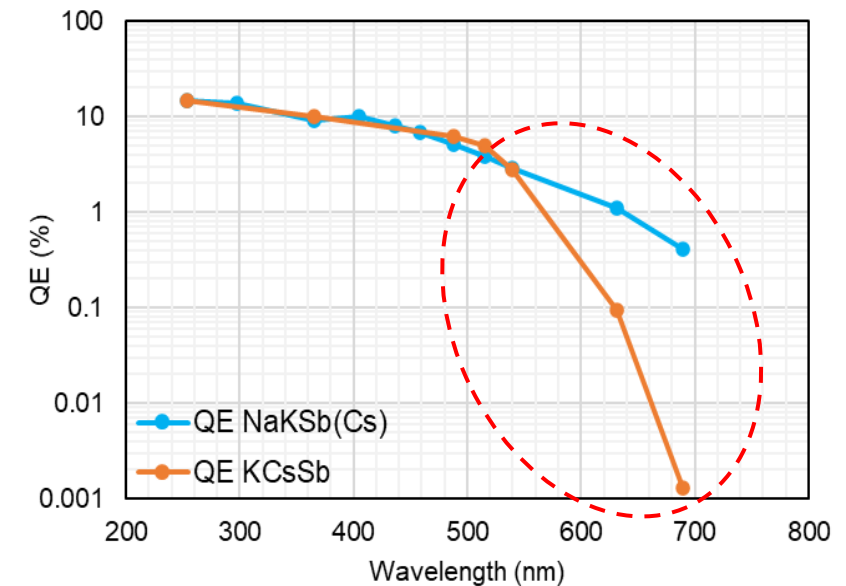
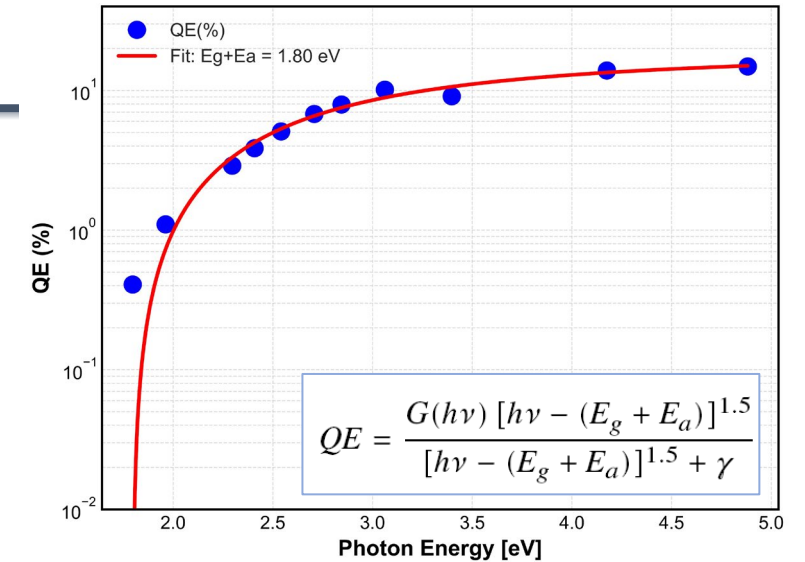
NaKSb(Cs) preparation

- One **NaKSb(Cs)** cathode (cathode 128.2) was produced through **sequential deposition** in the new preparation system at LASA.
- QE Achievement: QE of **3.7 % at 515 nm** for NaKSb(Cs).
- The estimated **$E_g + E_a$** value of NaKSb(Cs) is **1.8 eV**.
- Spectral Response Comparison: **NaKSb(Cs)** exhibits an **improved QE** at higher wavelengths compared to KCsSb, particularly in response to **red laser light**.

- Sb until reflectivity drops to 30 % from the initial value.
- K and Na deposited sequentially at 120 °C and 90 °C respectively until the QE reached a maximum value.
- To restore the correct Na:K ratio, a small amount of Sb and K were added in an alternated manner until the peak of QE was obtained at 90 °C.
- Then Cs was deposited until the sensitivity reached a maximum value at 90 °C.

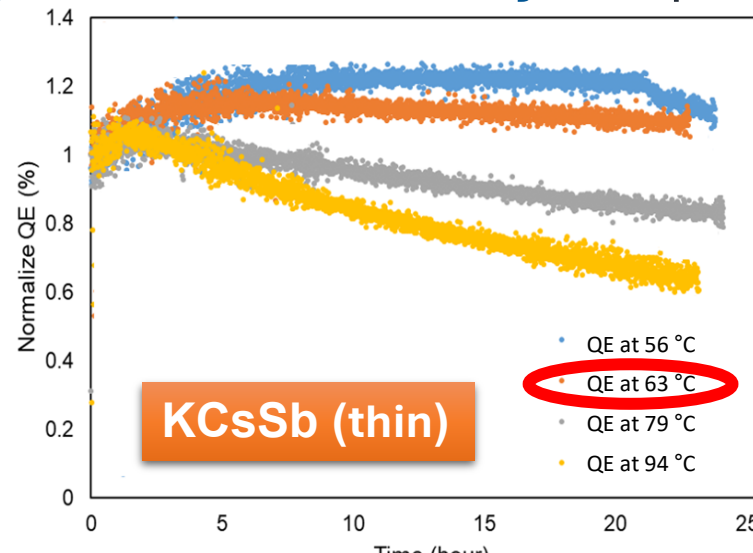
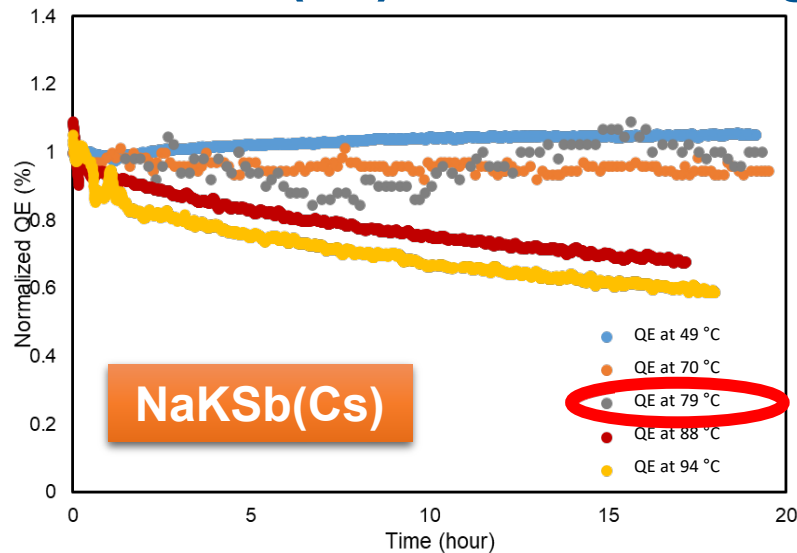


NaKSb(Cs)



Thermal robustness

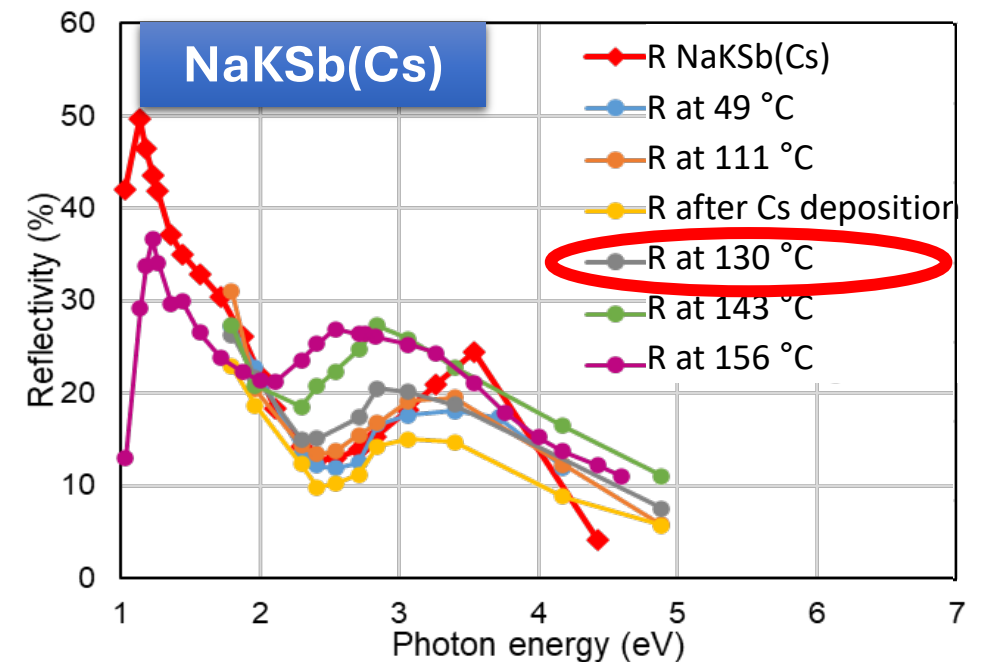
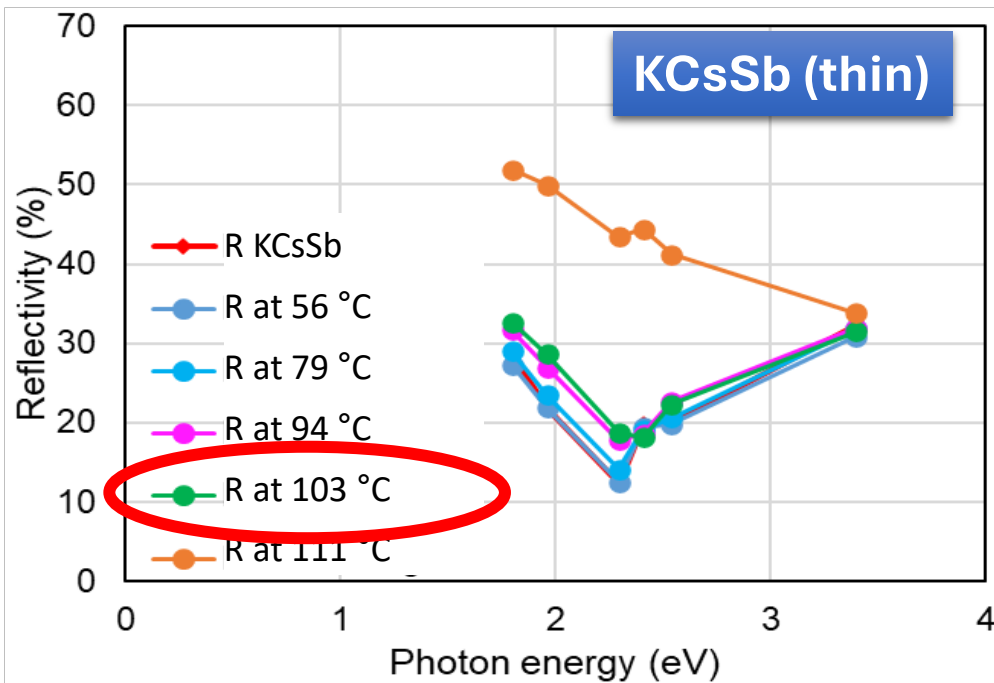
- Operation of photocathodes in RF guns or at high extracted charge has motivated an investigation of the thermal response of these photocathode to substrate temperature increase.
- **Lifetime comparison at different substrate temperatures:**
 - **NaKSb(Cs)** cathodes can withstand temperatures **up to ~79 °C**.
 - **KCsSb** cathodes can withstand temperatures **up to ~63 °C**.
- **NaKSb(Cs)** cathode has **higher thermal stability** compared to the **KCsSb** cathode.



Temperature (°C)	NaKSb(Cs) Life-time [h]	KCsSb Life-time [h]
79	> 1000	103
94	42	38
103	28	22

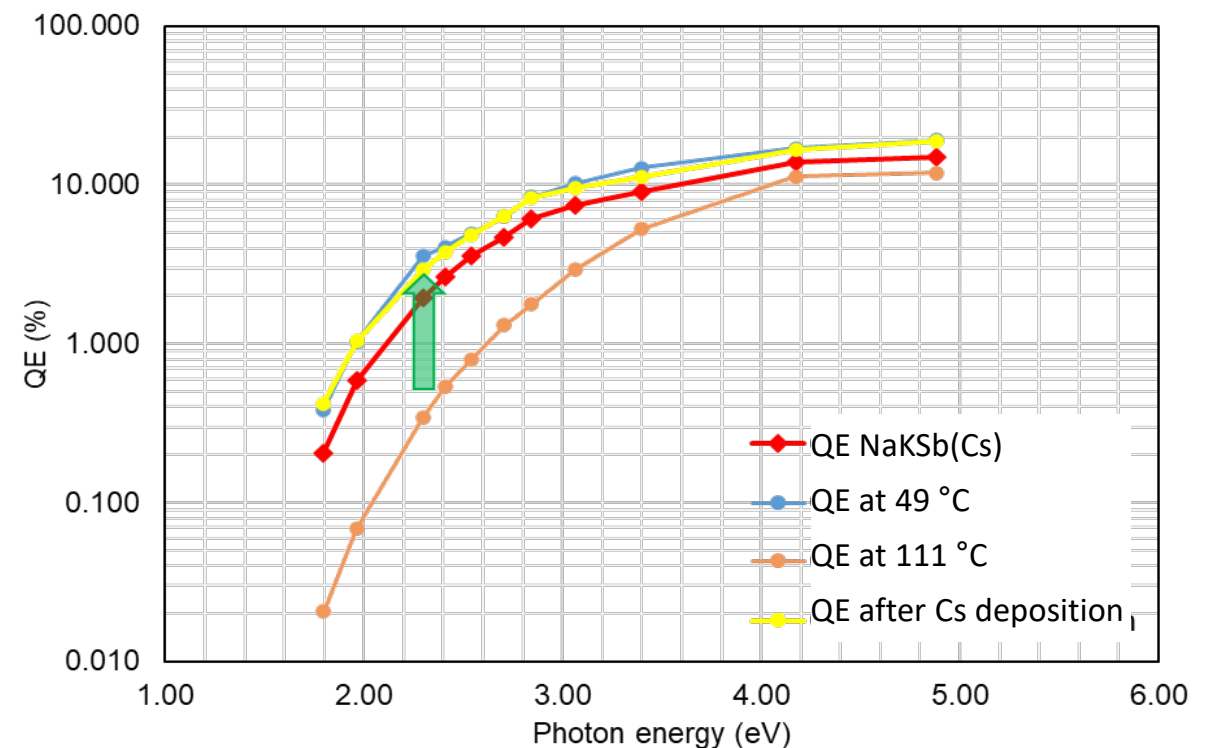
Temperature stability

- Reflectivity analysis shows **electronic structure stability** up to:
 - 103 °C** for **KCsSb**
 - 130 °C** for **NaKSb(Cs)** (same Sb thickness)



NaKSb(Cs) Rejuvenation by Cs

- After heating the cathode to 111 °C, **a few nm of Cs** were **re-deposited** onto the cathode surface.
- **QE across all wavelengths recovered to above original level**, demonstrating **effective rejuvenation** of the photocathode
- In some cases, the QE after rejuvenation might be even higher than the original one.



MC Simulation of QE using DFT Optical Constants

- **Objective**

- Model spectral quantum efficiency (QE) of K_2CsSb photocathode
- Use **DFT-derived $n(E)$, $k(E)$** as input for realistic optical response

- **Goal**

- Simulate spectral QE of K_2CsSb using **DFT n , k**

- **Model (3-step photoemission)**

- **Absorption:** $R(E)$, $\alpha(E)$ from DFT + Urbach tail
- **Transport:** MC with e-e, elastic, inelastic scattering
- **Emission:** Surface escape with energy-dependent transmission

- **Key Features**

- Energy-dependent $\eta(h\nu)$, scattering, and escape probability
- Adaptive Monte Carlo statistics

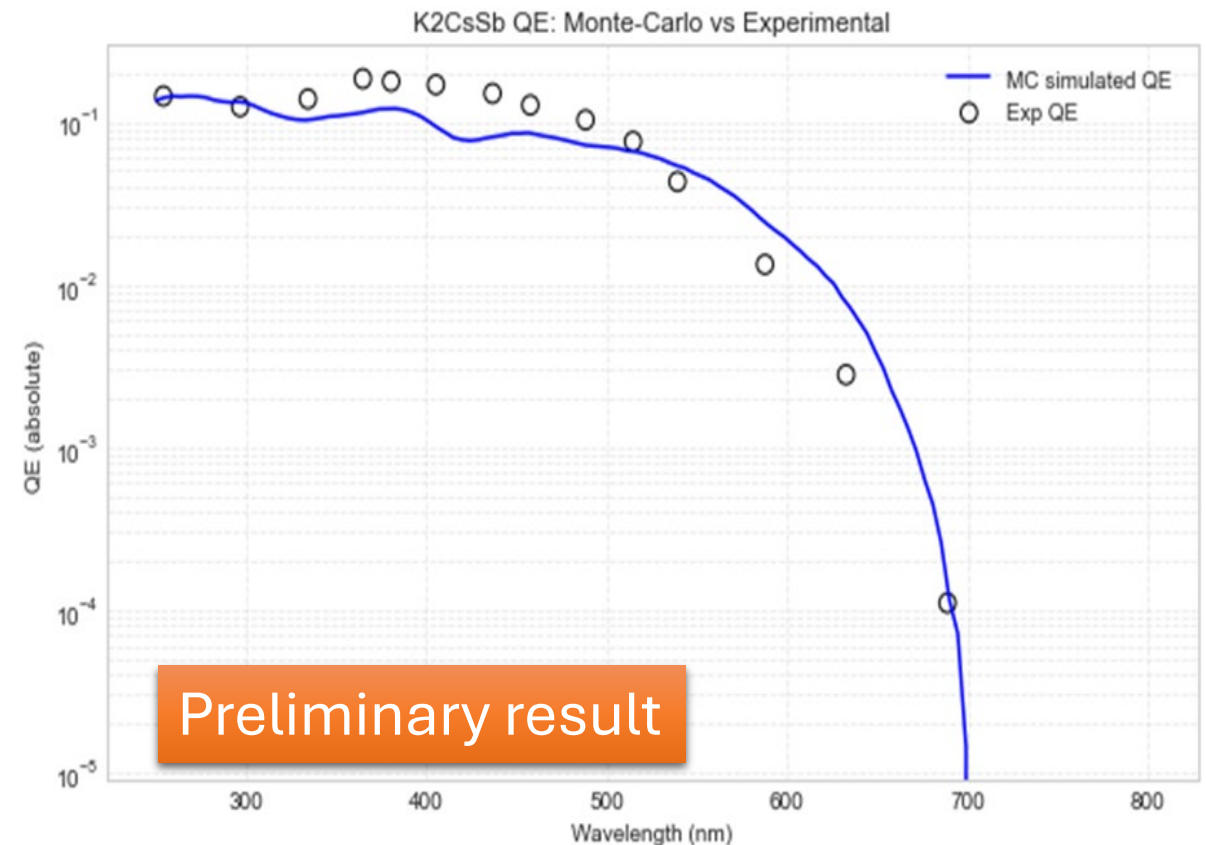
- **Results (Preliminary)**

- **Good agreement with experimental QE trend**
- Captures:
 - UV enhancement
 - Sharp cutoff near bandgap
- Remaining deviation at high wavelength

- **Future Work**

- Emittance modelling
- Stoichiometry variation analysis

Sandeep on-going work



Preliminary result

Conclusions

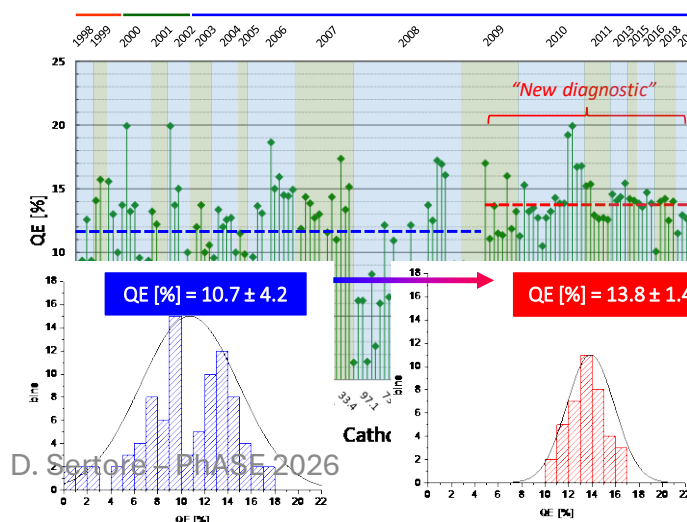
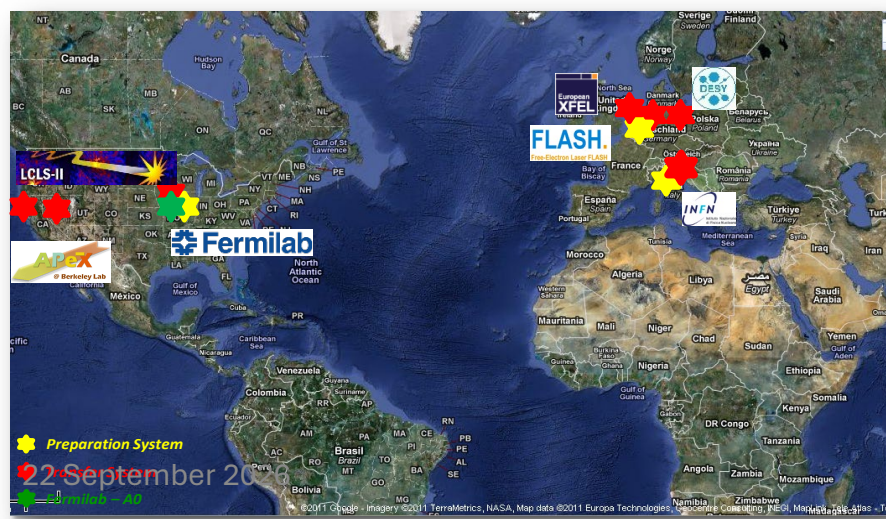
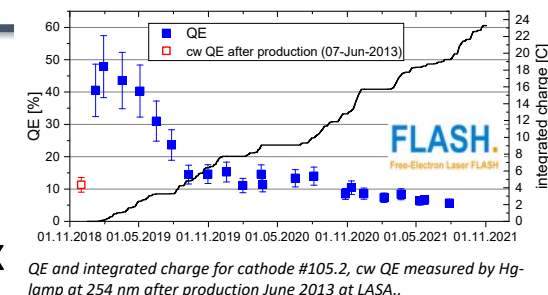
- **BriXSinO** will be an **important opportunity** for INFN LASA
- **HB²TF**, the first phase, is **successfully in progress** and we expect soon to have the first electron beam
- **HB²TF** use “**INFN**” **plugs** and its transport boxes. Testing of **different films is one of its applications**.
- Photocathode development towards further **understanding of the NaKSb(Cs) properties is on-going**, supported also by the development of a “first principle” photoemission model.

BackUp Slides

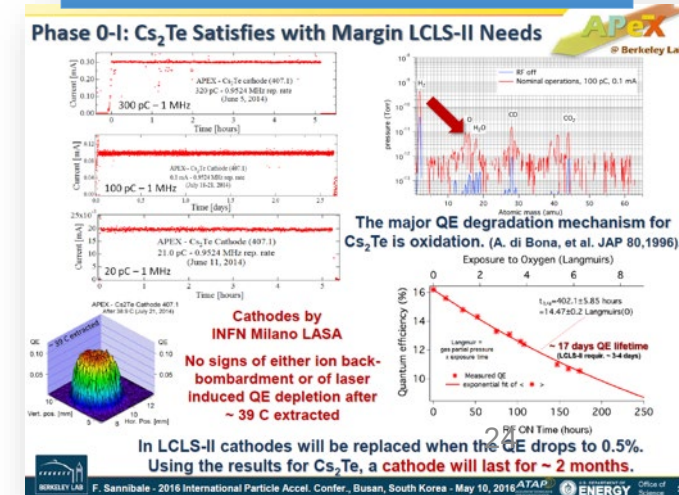
INFN LASA Cs₂Te Photocathodes

- INFN LASA produces Cs₂Te photocathode since 90s and it's a reference lab
- With a continuous interplay between collaborators and R&D, we today growth cathodes with an **operational lifetime (24/7)** in the user facilities increased **from few months to few years**, that are a **reference for many accelerator complex**
- More than **150 photocathodes** delivered up to now
- Cs₂Te photocathodes have been demonstrated **usable** also for **CW operation**
- Facilities/injectors: **FLASH** and **PITZ** (DESY), **FAST** (FNAL), **APEX** (LBNL), **LCLS-II** (SLAC)
- **INFN Mo plug** is now a **"standard"** allowing exchange of photocathodes between facilities: **EU** (DESY, STFC), **US** (FNAL, LBNL, BNL, SLAC, UCLA, Cornell), **China** (IHEP, SHINE, Dalian)

Extracted charge: ~ 23 C
1063 days of oper. until now

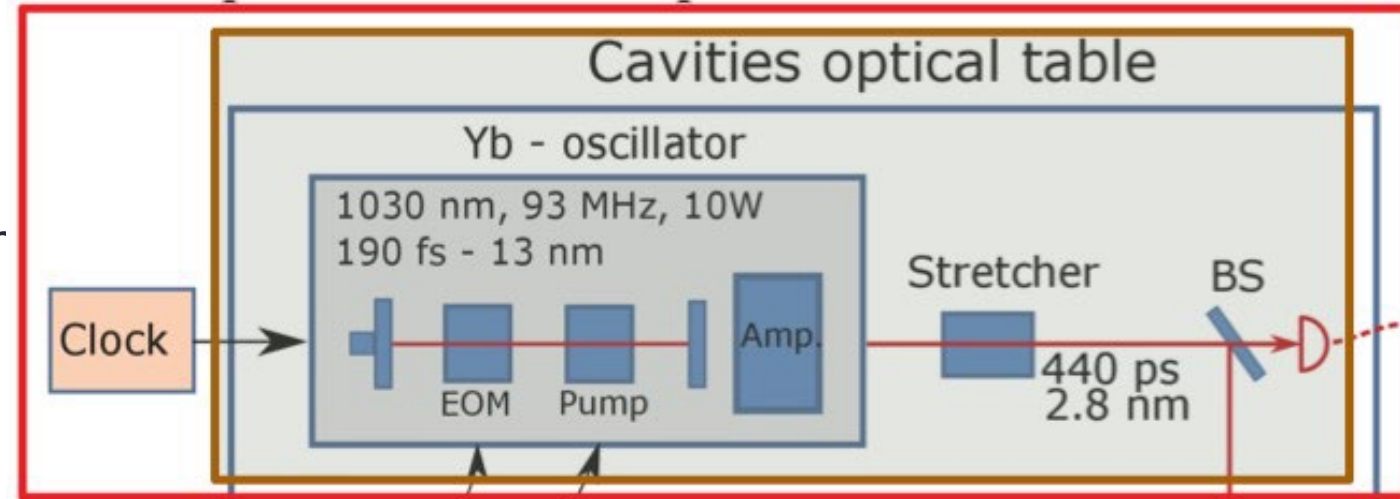


CW (1 MHz) operation in APEX gun



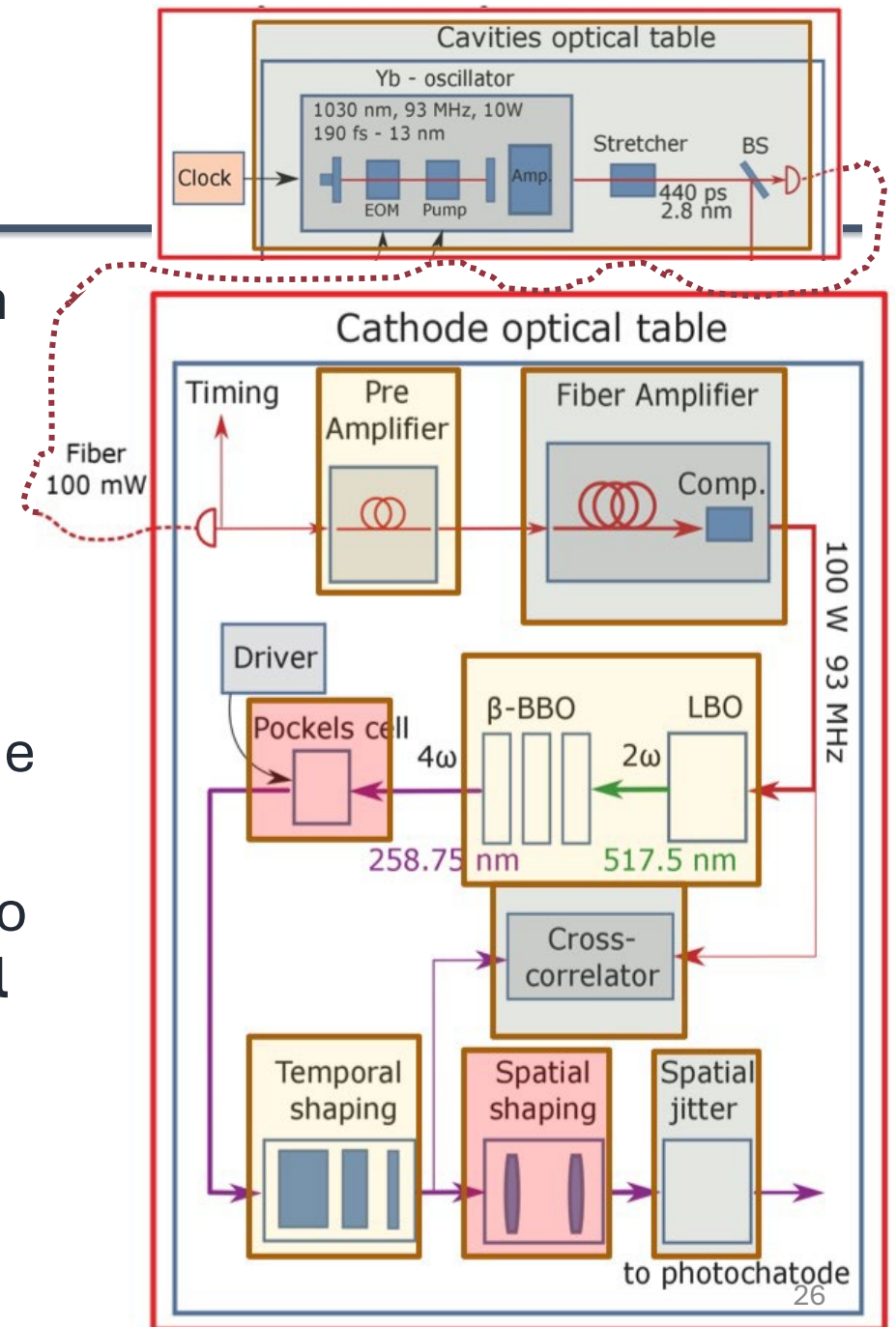
Laser scheme

- The **aim** of the optical system is to **excite the photocathode** for the generation of the electron bunches.
- The **main oscillator** is a **1035 nm** mode-locked Yb laser with a **92.857 MHz** repetition frequency (7th sub-harm of 1.3 GHz).
- An internal amplification system guarantees a **maximum output power of 10 W**, with a spectral width of 13 nm and a pulse duration of **190 fs**.
- The **pulses** from the oscillator are temporally **stretched** by a Chirped Volume Bragg Grating (CVBG) up to **440 ps**, with a spectral width of 2.8 nm.
- **After this stretching** stage, a **100 mW** laser power is **coupled into a fiber** (about 30m long) and then used for the photoemission process.



Laser scheme

- The **100 mW** laser pulses are amplified using a **2 stage** process **up to 60 W**.
- The high power pulses are **converted from IR to the 4th harmonic** at 258.75 nm to obtain pulses suitable for the Cathode Material.
- The **repetition rate** of the laser pulses is **controlled by a Pockels** cell from kHz up to the repetition rate of the oscillator.
- Subsequently, the 4th harmonic pulses undergo an intensity **profile shaping, both in temporal and spatial domains**.



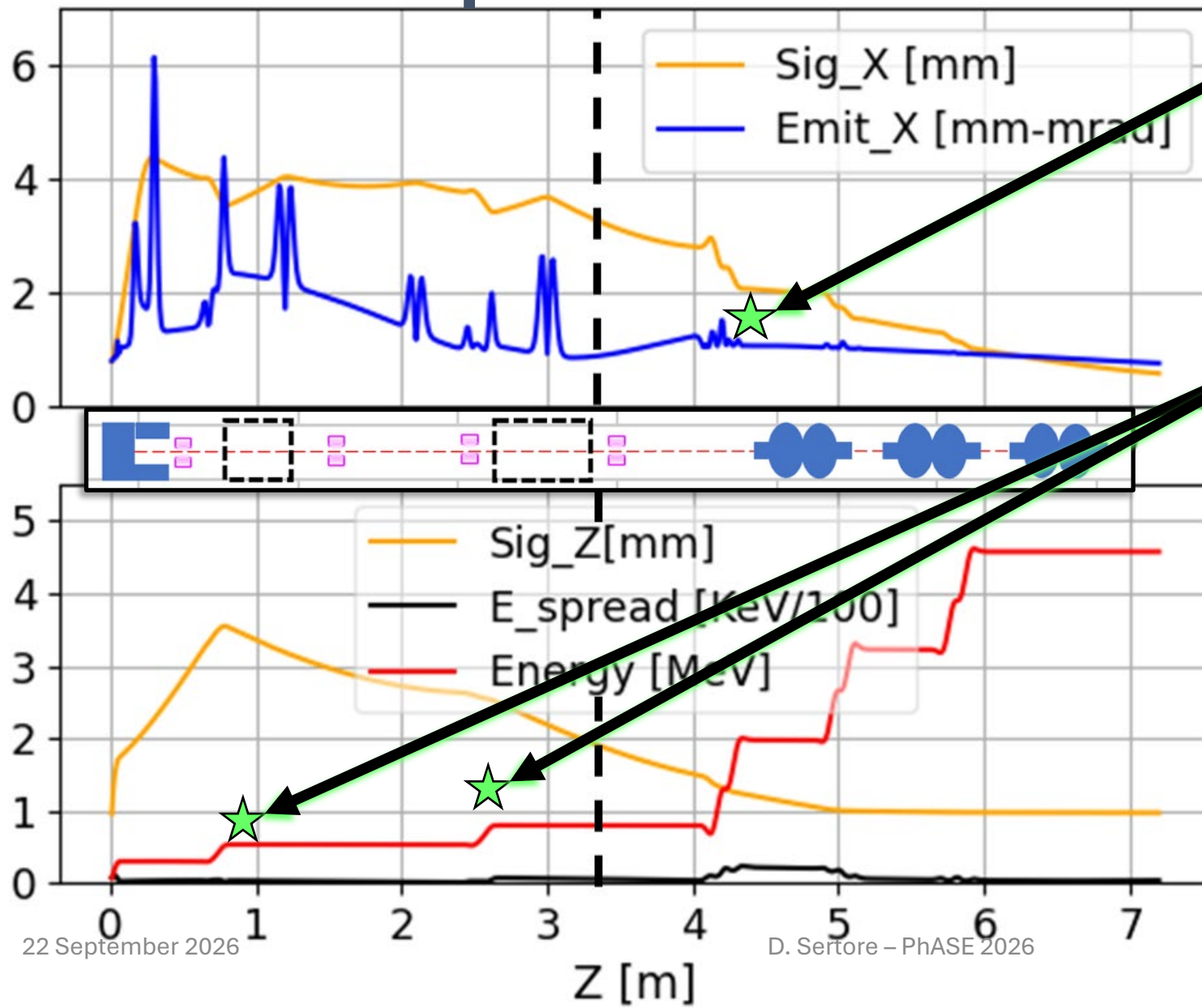
Beam Physics

- The beam dynamics study developed for this project aims **to design an injector** that in a near future **will be used for an ERL**.
- This concept can be made explicit as follows: **beam energies as low as possible** (they will never be recovered) compatible with a **beam brightness high** enough to drives experiments.
- In this view, the beam dynamics studies carried out aimed to **couple the injector of HB²TF to a SC booster** to produce a beam with energy of 4.5 MeV, an emittance of about 1.2 mm- mrad and a rms bunch length of about 1.2 mm.
- To obtain **high brightness beam** it is of paramount importance to keep **emittance growth under control**.
- **Low energy and high brightness results into a BD space charge dominated that is one of the points of interest of this proposal.**

Beam Manipulation

- This design is **innovative** because it uses **two bunchers instead of one** and employs a **650 MHz** rf frequency **instead** of the commonly used **1.3 GHz**.
- The choice to use a **longer rf bucket** allows for the trapping of **longer cigar-like electron bunches** having lower emittances. Additionally, the use of **two bunchers** provides **better control** over **longitudinal bunch compression**.
- The **injection phases** of the two bunchers are not at the rf zero-crossing, allowing for **acceleration** while mitigating space-charge effects and bunching to increase the final beam brightness.
- The whole HB²TF **beamline** has been **studied** using the tracking code **Astra** that is designed to consider space-charge collective effects, a key point for HB²TF beam dynamics, further the beam line working point (WP) has been **optimized using an AI** code already developed in our group named **GIOTTO**.

Beam Manipulation



SC booster
emit-compensation in
space charge regime:
 σ_x & ϵ_n behaviour well
tuned

Bunchers
compression &
acceleration

Bunch extraction:

$Q_b = 50$ [pC]; $\sigma_{x,y} = 650$ [μm]; $\tau_{\text{laser}} = 18$ [ps] (rise-time = 1ps)

DC-gun:

$\Delta V = 300$ kV

The two Bunchers:

$E_p = 2.7$ MV/m $\Phi_{\text{inj}_1} = -31^\circ$, $\Phi_{\text{inj}_2} = -35^\circ$

SC inj. booster (three two-cells):

$E_p = 11.5$ MV/m $\Phi_{\text{inj}_1} = -25^\circ$, $\Phi_{\text{inj}_2} = 21^\circ$, $\Phi_{\text{inj}_3} = 0.0^\circ$

beam-line solenoids peak fields [T]:

$B_{z_1} = 0.0276$, $B_{z_2} = 0.0172$, $B_{z_3} = 0.0128$, $B_{z_4} = 0.0246$

