Second TDR Review Committee Meeting
Zoom, October 26th, 2021

WA2 - Injector *Status Report*

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on behalf of WA2 contributors

Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

WA.2: Injector

- **Coordination and promotion of activities and components** related to the injector as developed by WPs involved, i.e.
  - WP01: **Accelerator Physics** (Giribono, Mostacci)
  - WP08: **RF gun and accelerating structures** (Piersanti)
  - WP10: **Vacuum** (Liedl)
  - WP11: **Lasers & Cathodes** (Anania)
  - WP12: **High Power RF & Distribution** (Cardelli)
  - WP14: **Beam Instrumentation & electronics** (Stella)
  - WP15: **LLRF & Synchronization** (Bellaveglia)
  - WP16: **Control System & Interlocks** (Stecchi)
  - WP17: **Magnets & Power Supplies** (Sabbatini)
  - WP18: **Undulators** (Petralia)
  - WP19: **Mechanical Engineering** (Pellegrino)
  - WP21: **Cooling & Ventilation** (Cantarella)

WA.2 Roadmap to the TDR

Nov. 2020: WA.2 Kick-off Meeting

October 2021: ***Commissioning of the new RF gun*** *at SPARC_LAB*

February 2022: ***Simulation studies*** *on main WoPs*

March 2022: *3D CAD Design of the* ***photo injector layout and laser transport line***

June 2022: *R&D on* ***High Rep Rate Gun***

June-Sept. 2022: *Project of the* ***photocathode laser*** *and test at SPARC_LAB of laser pulse shaping (both transverse and longitudinal) and diagnostics*

Oct. 2022: ***Laser Heater*** *project*

Dec. 2022

Jan.-Feb. 2023: ***R&D on 11.994 GHz*** *Klystron @100Hz and test on X-band structures*

Mar. 2023: *Studies and tests at SPARC_LAB on* ***RF jitters*** *(Upgrade of LLRF and synchronization system; procurement and tests of S-band SSM)*

May 2023: ***Diagnostics*** *prot., fabrication and tests at SPARC_LAB*

Dec. 2023: ***TDR completion***

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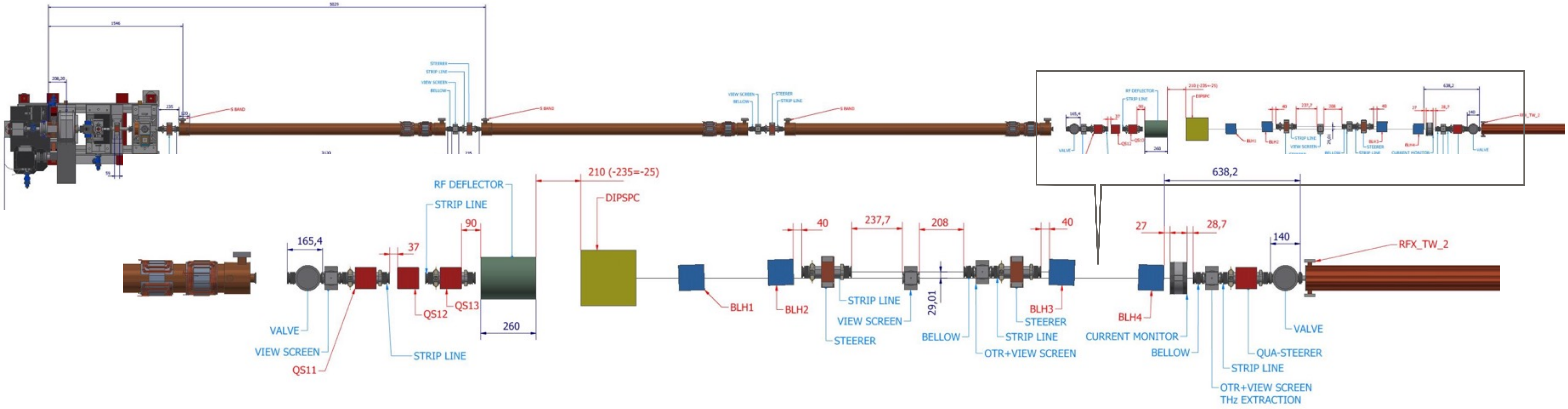
Current injector layout

- Phase 0 **Layout** has been defined
  - SABINA photoinjector up to the end of the 2 S-band TW accelerating structures
  - 1 more S-band TW linac layout up to the laser heater inserted in the TStep model



Benchmark with different codes

The machine model has been implemented in ASTRA

- High charge WP cross-checked

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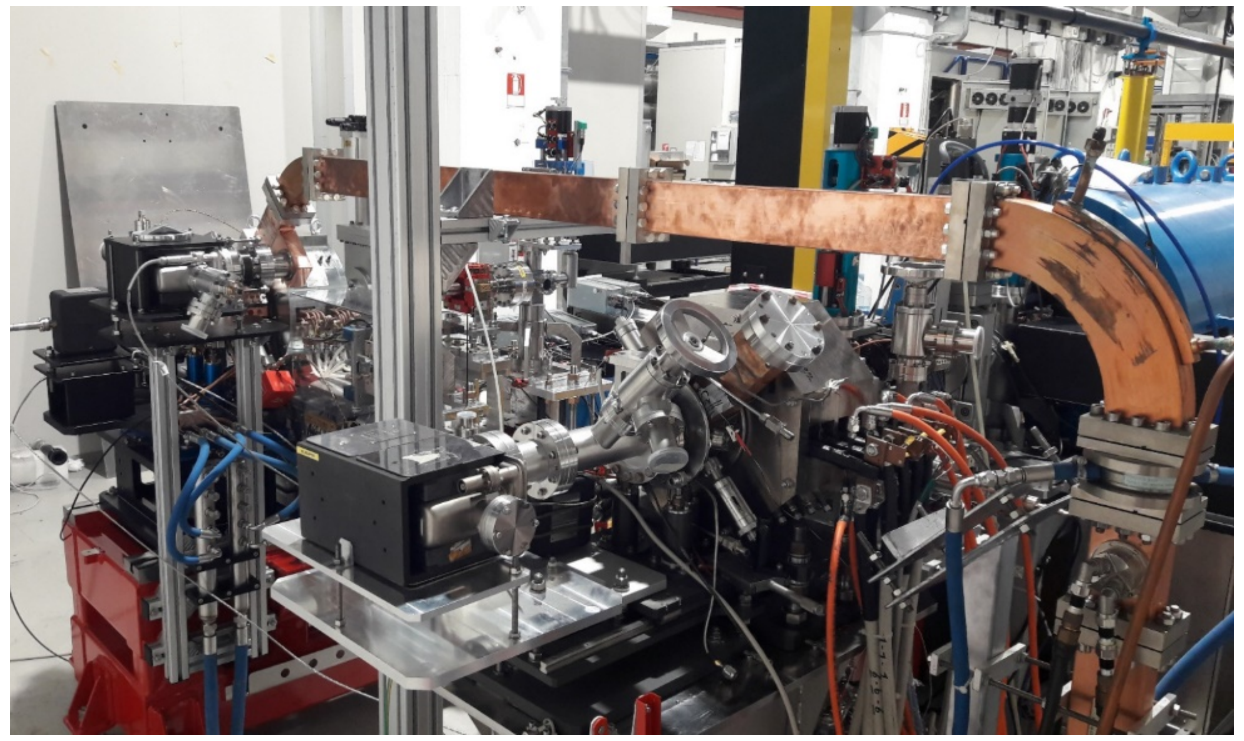
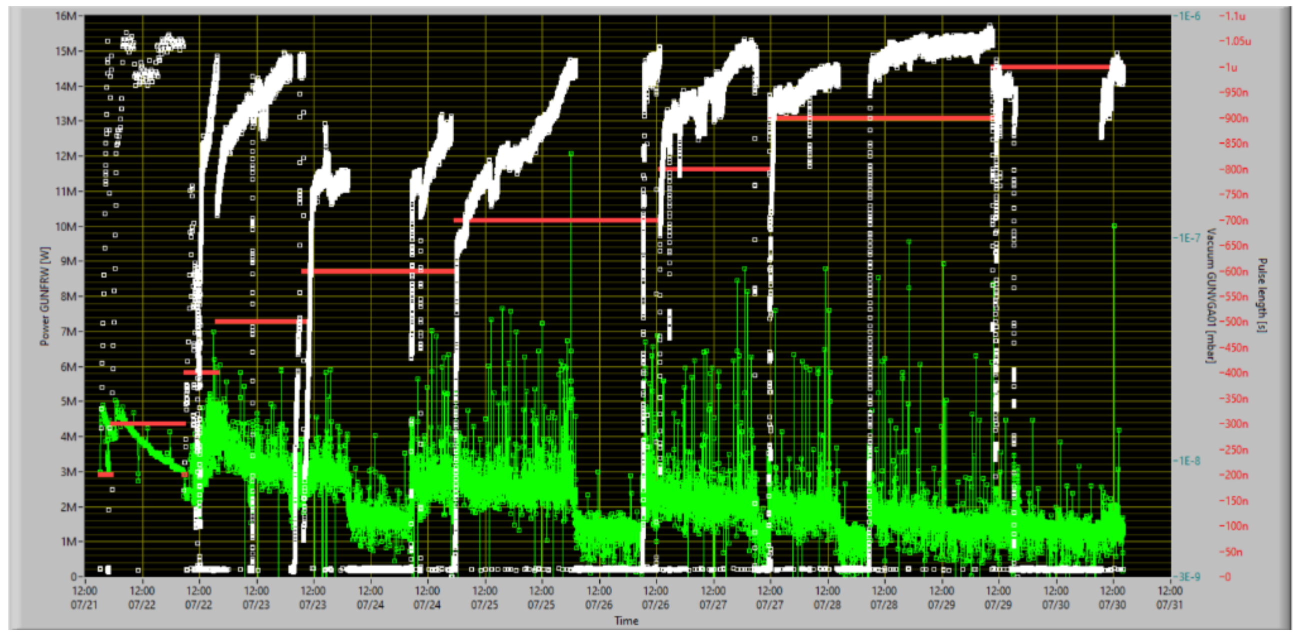
SPARC_LAB RF Gun upgrade

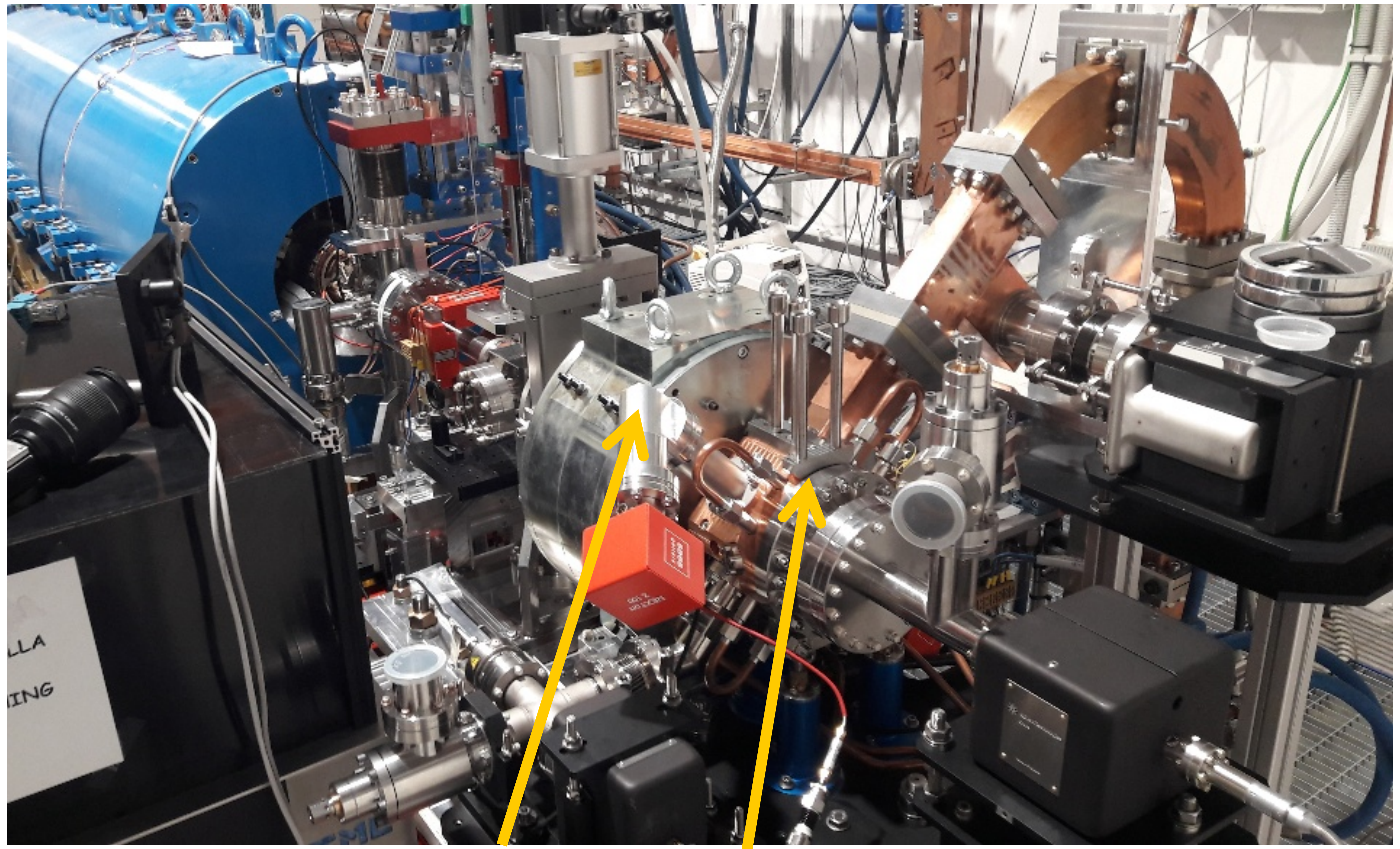
Courtesy of D. Alesini

- The injector has been tested at high power on a RF parallel line, reaching the final performances in an incredible short time (< 10 days)
  - Reached full power (**15 MW**) at nominal pulse length (**1 us**) and repetition rate (**10 Hz**)→**120 MV/m** peak electric field on the cathode
- The new injector has been **now inserted online** and RF test will start in these days following by electron generation and beam characterization

New injector under test on a parallel line



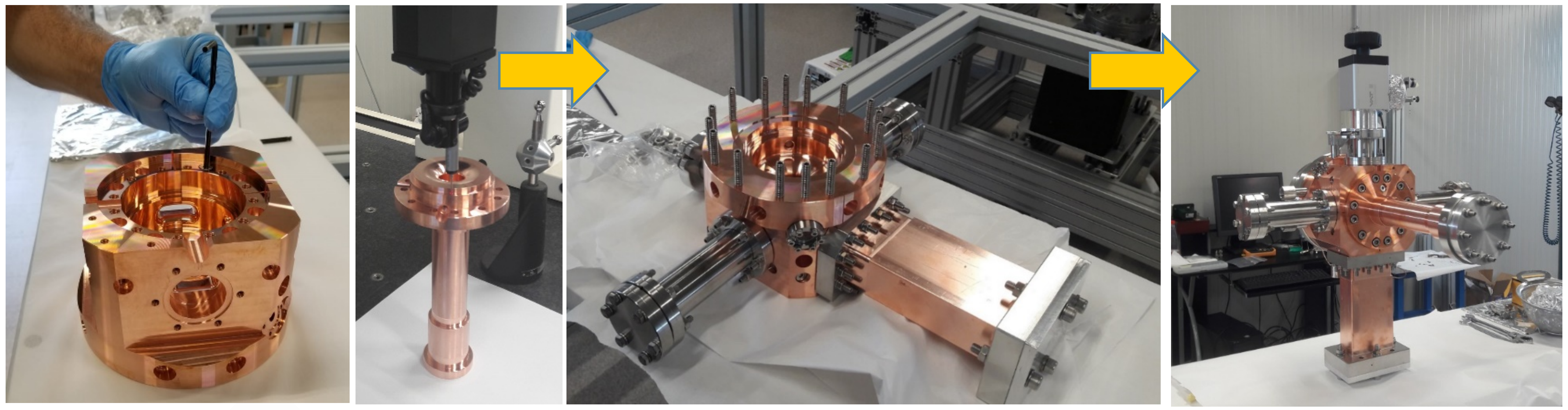


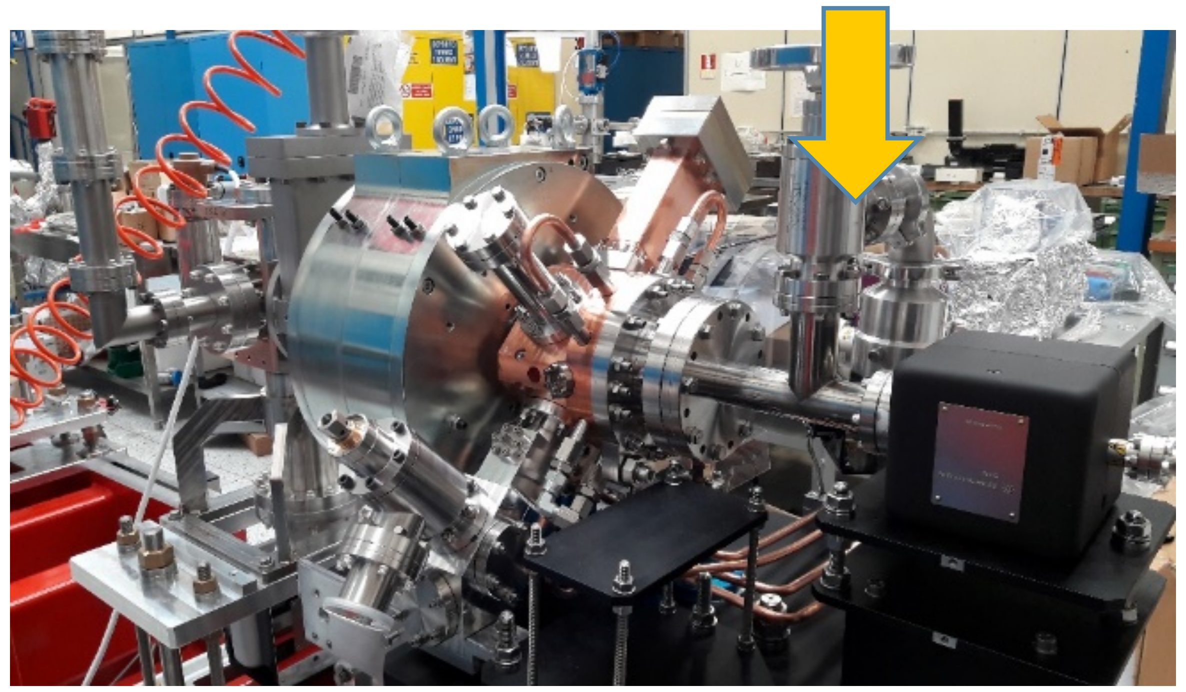


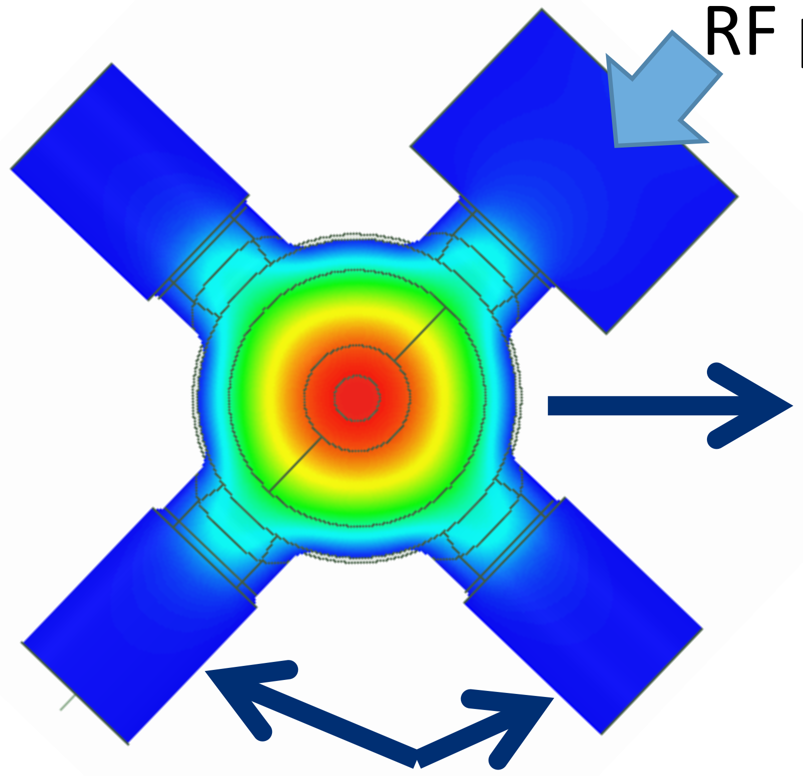
Improvements implemented

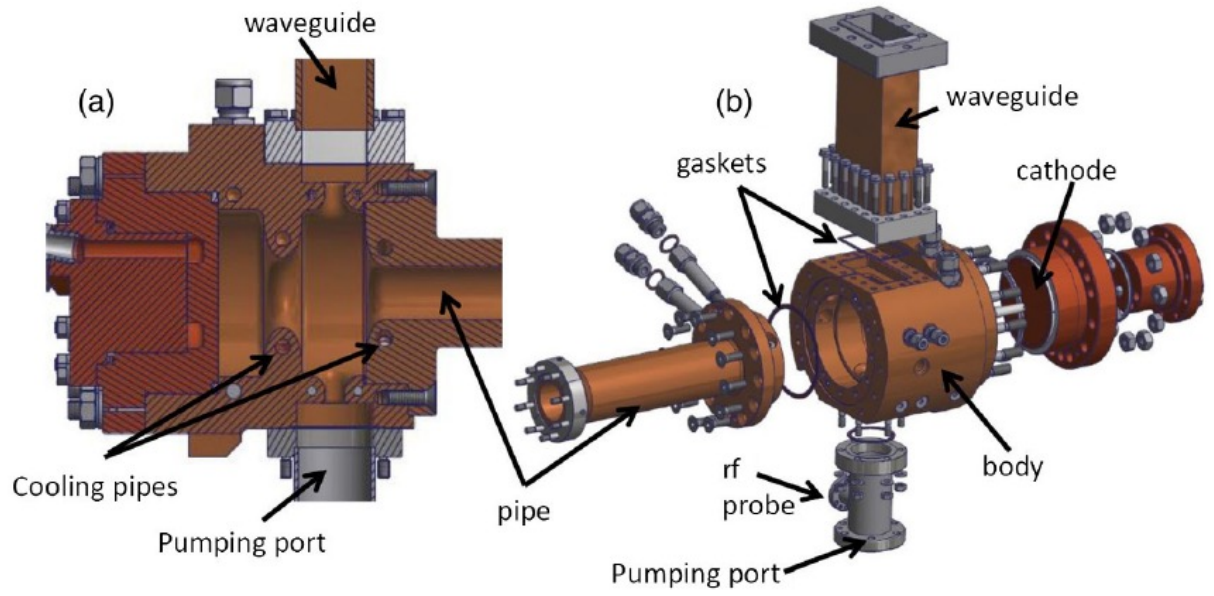
Courtesy of D. Alesini

- With respect to the "old" injector the new one: Integrate an RF gun fabricated with the **new brazing free technology**;
- Integrate a new solenoid with a remote control of the transverse position at the <+/-10 m level;
- allows **on axis laser injection system** with the last mirror in air and not into the beam pipe;
- Has been designed with the possibility of a future integration of an X/C band cavity linearizer;
- Has a **variable skew quadrupole** after the gun for the compensation of residual quadrupole components
- Has an electromagnetic design with a full compensation of the quadrupole components
- Has an improvement of the effective pumping speed with two added pumping ports
- No cathode tuning is necessary









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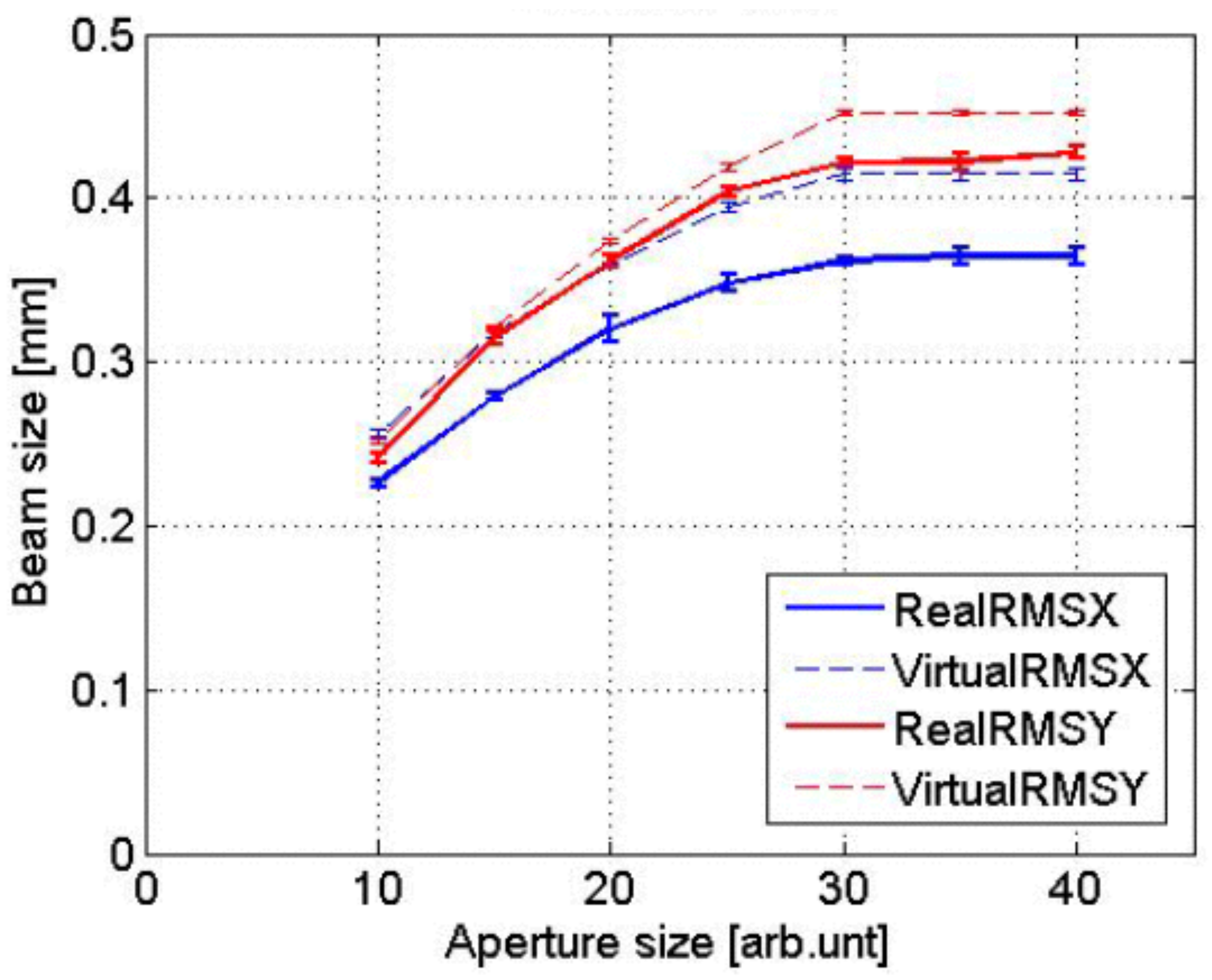
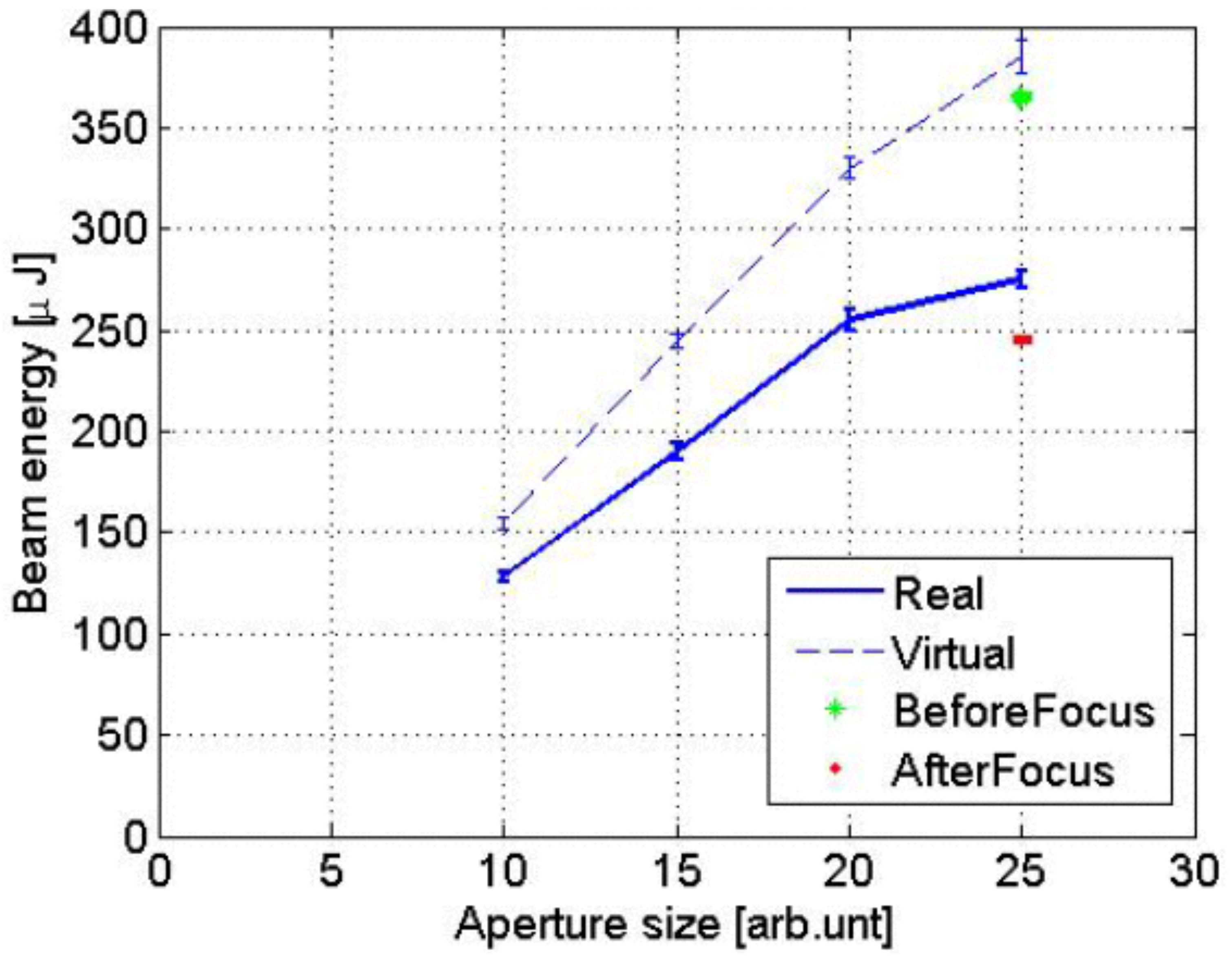
Laser Transport Line

Courtesy of V. Shpakov, M. Galletti

- The laser transport line has been defined and it is in place
- Measurements to directly compare virtual and real cathode have been performed
  - The real (copper) cathode has been replaced with YAG crystal to measure the laser spot size and with a joule meter to make direct energy measurements
  - Measurements were conducted simultaneously at both real and virtual cathode





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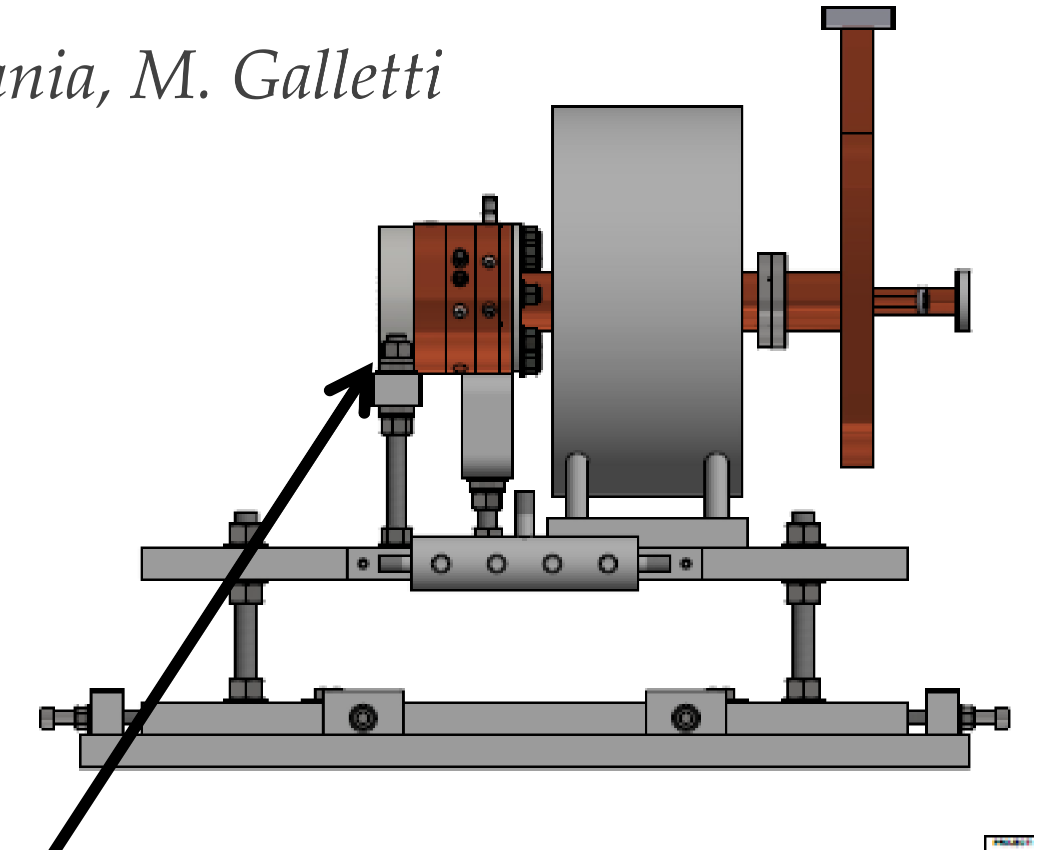
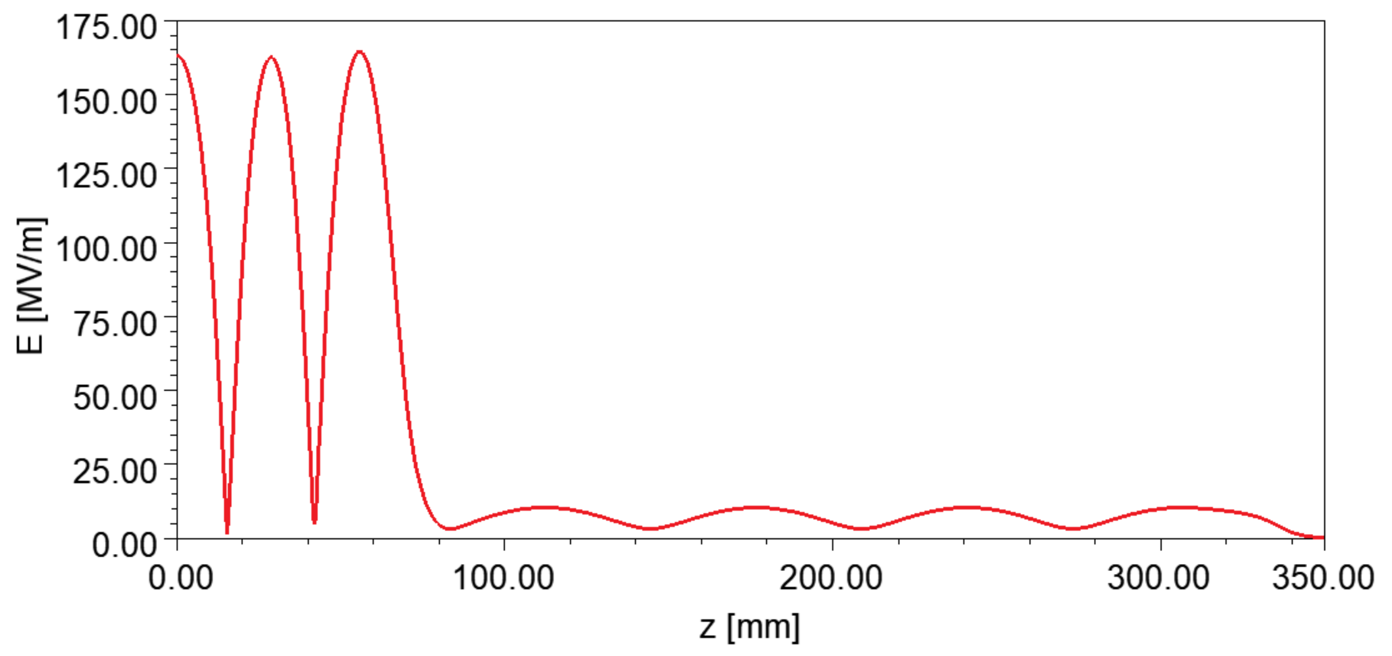
Operation at 400 Hz

Courtesy of D. Alesini, M.P. Anania, M. Galletti



- In the framework of **IFAST (Horizon 2020) and TUAREG (INFN Commission V)**
  - **C band gun and full C band injector** (gun + TW C band structures)
    - **very promising** in terms of achievable beam parameters, compactness and possibility **to go at very high repetition rate** (up to 1 kHz)
- High rep rate photo-cathode laser
  - ARCO M (Amplitude) for a high rep rate laser from the t_0

	ARCO M
Repetition Rate	1 kHz
Energy Per Pulse	5 mJ / 10 mJ / 20 mJ
Average Power	5 W / 10 W / 20 W
Pulse width	< 100 fs / 35 fs / 20 fs



- Semiconductor cathodes might not be suitable both for the long temporal response and for the unsustainable high peak field at the cathode (max 100 MV/m to be verified)
  - Metal cathodes with the 2nd harmonic (SHG) of the Ti:Sa —> 400 nm
    - Preliminary tests at SPARC_LAB with Cu
    - Yttrium studies at Fermi@Elettra

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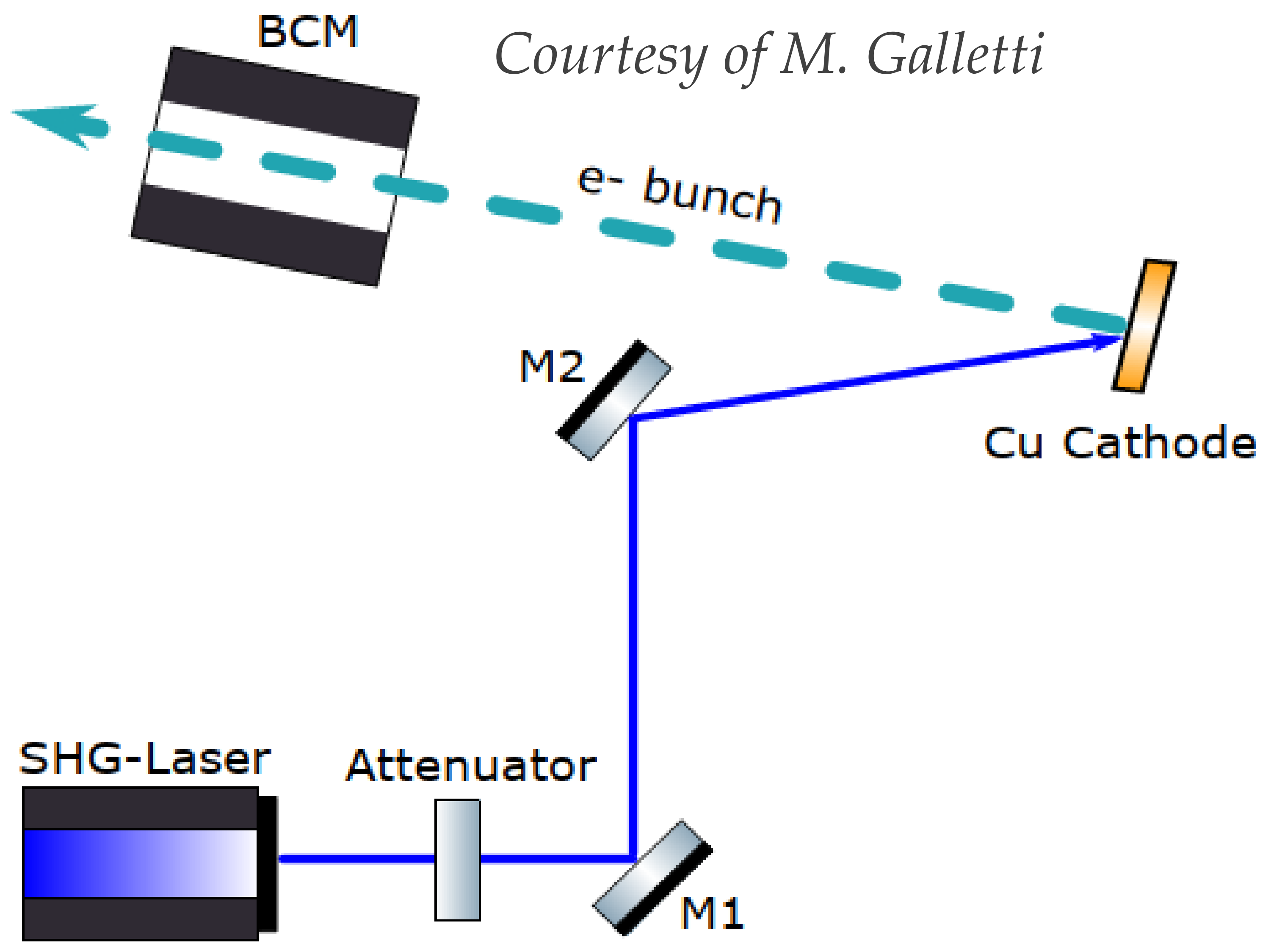
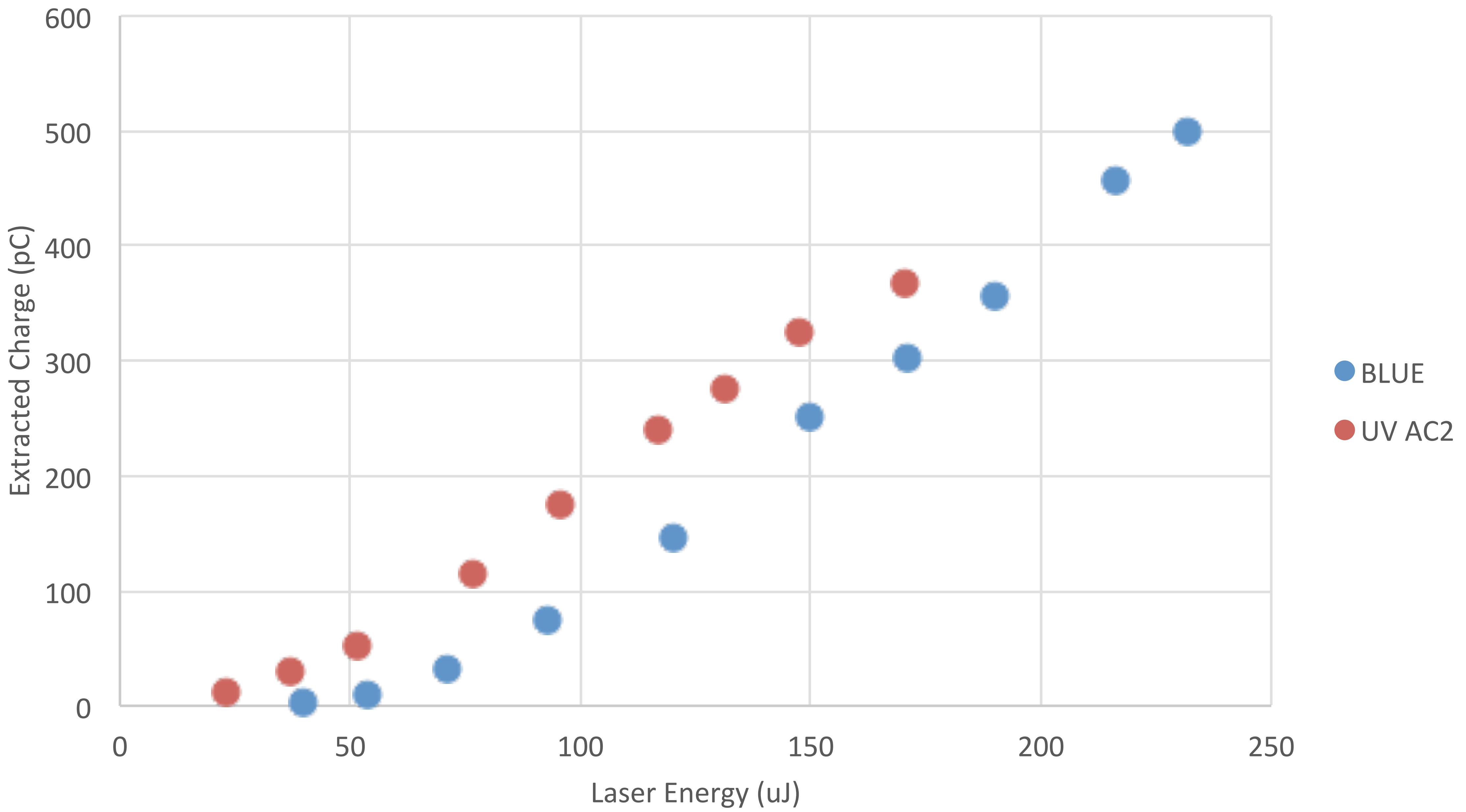
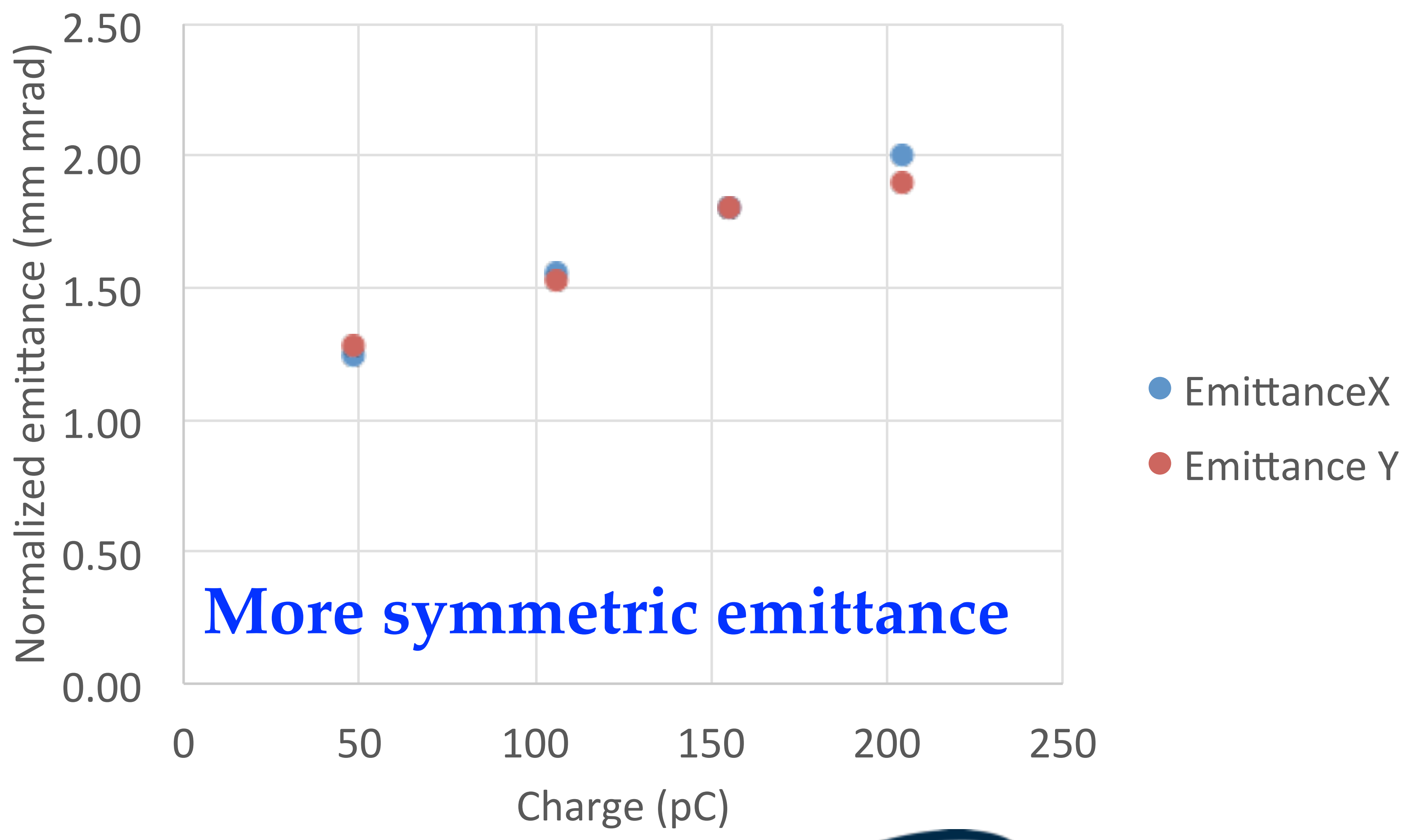
SHG Photo-Cathode Laser

- **Photoelectrons by means of “blue” laser wavelength**
- The dominant contribution has been demonstrated to be the two-photon photoemission process
- Simplification of the current laser setup (namely transport, diagnostics)
- Increasing energy, transverse homogeneity and temporal stability of the laser







R. Pompili, et al. "Time-resolved study of nonlinear photoemission in radio-frequency photoinjectors," Opt. Lett. 46, 2844-2847 (2021)

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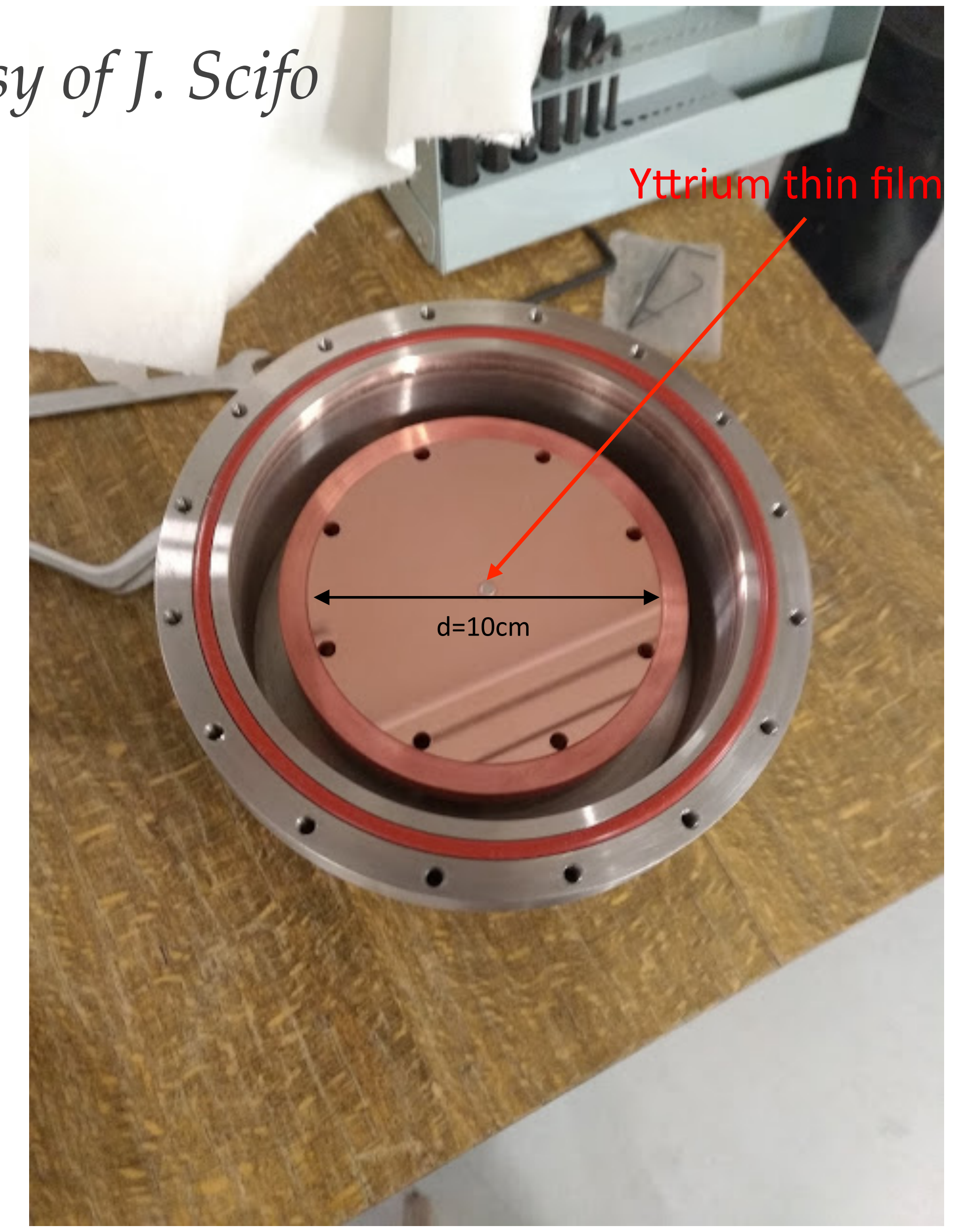
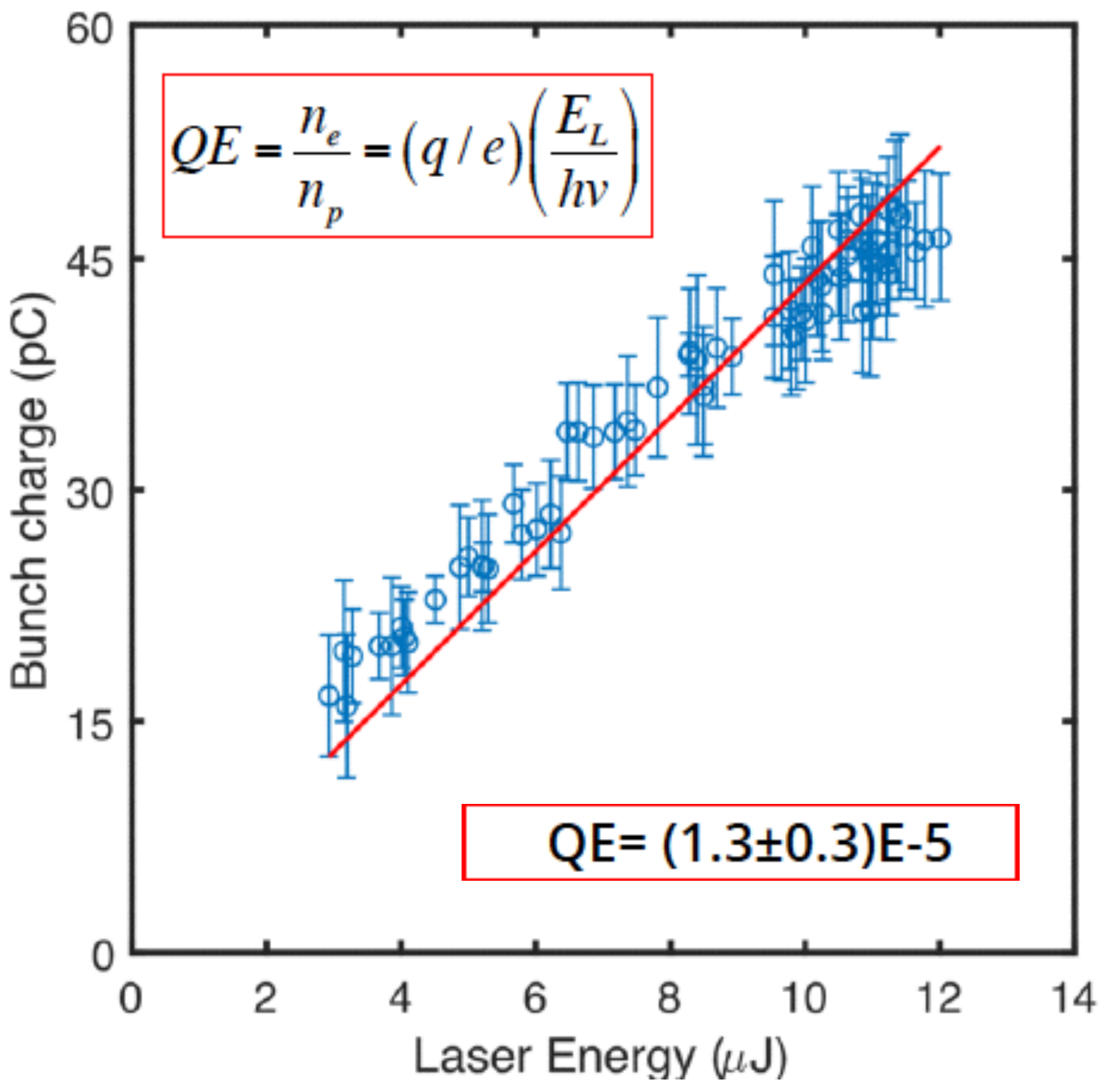
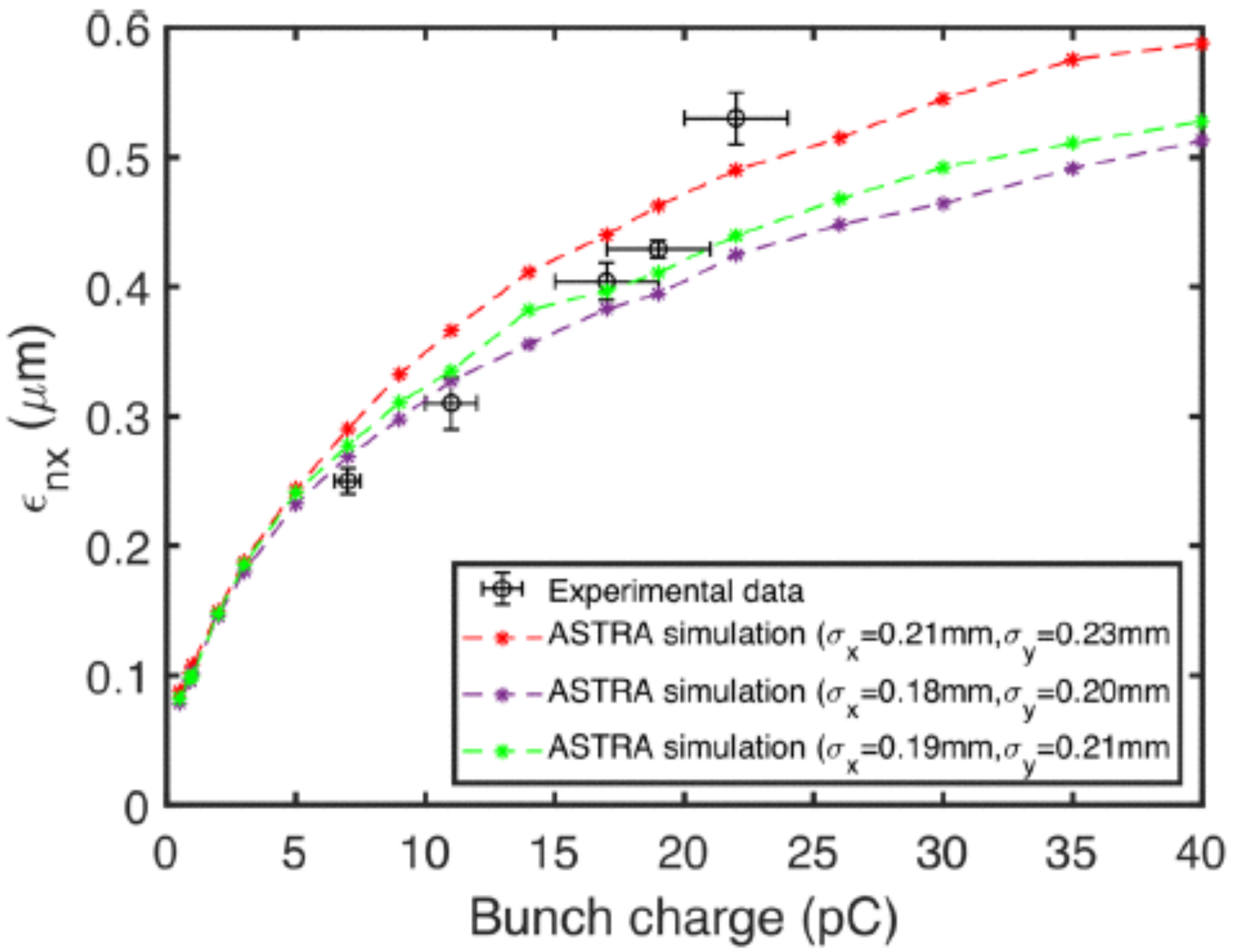
Yttrium Studies at Fermi@Elettra

Courtesy of J. Scifo



- A yttrium (Y) thin film (1.2 μm thickness and d = 3 mm diameter) was grown by pulsed laser deposition (PLD) on a copper (Cu) polycrystalline photo-cathode [1] . The deposition has been done in the centre of the flange.
- PLD of yttrium on copper guarantees a film highly adherent and with high quality [2].
- Yttrium is a transition metal that has a work function of $\phi_{work} \sim 3$ eV ($\phi^{Cu}_{work} \sim 4.6$ eV).





✓ Extrapolated value of Yttrium intrinsic emittance:
$\varepsilon_{intr,n}$= 0.46±0.02μm/mm

✓ Theoretical value of Yttrium intrinsic emittance:
$\varepsilon_{intr,n}$= 0.45μm/mm (λ_{laser}= 392nm)

J. Scifo et al., *Photoemi ssion studies of yttrium photocathodes by using the visible radiation.* PRAB 23.12 (2020): 123401.

A. Lorusso et al., Deposition of y thin films by nanosecond uv pulsed laser ablation for photocathode application, Thin Solid Films 603 (2016) 441–445.
A. Lorusso et al., Pulsed laser deposition of yttrium photocathode suitable for use in radio-frequency guns, Applied Physics A 123 (12) (2017) 779.

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Injector Simulations

Courtesy of A. Giribono

- Layout S-band injector optimization:
  - 3+3+2 vs 4x2m arrange ✓ ⇒ 3+3+ 2(3) each beam coming from ASTRA/Tstep is delivered at the first 2 s-band exit and at the third to be free with the Linac layout (i.e.: 2m o 3 m s-band upstream the LH) and to compare with Elegant
- Design of the x-band linearizer
  - Preliminary studies started
- Laser heater project
  - Subject to the definition of the injector

S-band RF Power Station

Courtesy of F. Cardelli

- Quotations for S-band waveguide components (from CML and MEGA RF), i.e. isolator, phase shifter and power divider, working at high power in high vacuum, to avoid SF6
- **DESY-like flanges prototype for WR284 S-band waveguide**.
  - Two prototypes have been realized and assembled. The Vacuum and baking tests on this prototypes have been performed successfully
- Definition of the number of S-band stations and choice of the klystron
  - It depends mainly on the **choice for the working frequency: EU 2998MHz or US 2856MHz**

Synchronization system upgrade

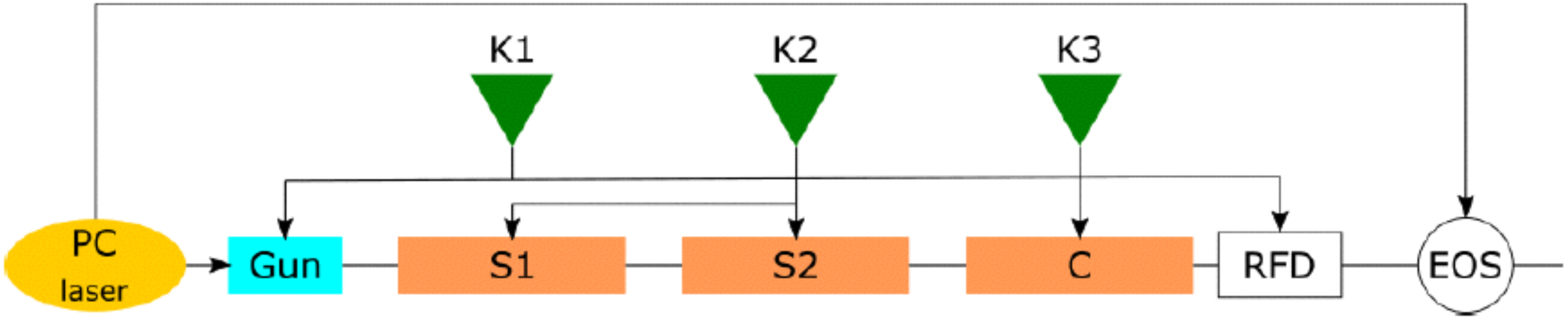
Courtesy of M. Bellaveglia

- Simulations to validate the theoretical model used for the jitter and crosscheck with measurements at SPARC
- Transition to optical system
  - Project request for cross-correlators for the transition to the optical system at SPARC_LAB
- New KlyLoop
  - New fast phase delays tested (reaction time <<1us) for the feedback system
  - Project of the amplifier on going
  - Test on the C-band SSM at SPARC_LAB foreseen to study the performance on short pulses in order to further minimize the iitter of a solid state klystron (~ few tens of fs)
  - Survey on possible development of digital electronics

Arrival Time Jitter: Model Validation

Courtesy of G. Giannetti, supervised by M. Bellaveglia and L. Piersanti

- The subsystems of a linear accelerator (laser, klystrons, etc.) are affected by a timing jitter Δt_i affecting the beam arrival time at the end of the linac, t_{linac}
- In the case of SPARC_LAB we have that:
  - the PC laser feeds the photo-cathode and the EOS (Δt_1);
  - Klystron 1 (K1, S-band) feeds the gun and the RFD (Δt_2);
  - Klystron 2 (K2, S-band) feeds the first two S-band accelerating sections S1 and S2 (Δt_3);
  - Klystron 3 (K3, C-band) feeds the last C-band accelerating section C (Δt_4).



- First order model for the beam arrival time difference: $\Delta t_{linac} \approx \sum_{i=1}^{4} c_i \Delta t_i$
- If $\Delta t_i = 1$ for $i = 1, 2, 3, 4$, $\Delta t_{linac} = \Delta t_i$ and we have that $\sum_{i=1}^{4} c_i = 1$
- First order model for the ATJ: $\sigma_{t_{linac}}^2 \approx \sum_{i=4}^{4} c_i^2 \sigma_{t_i}^2$
- Arrival time jitter (ATJ): standard deviation of the beam arrival time, $\sigma_{t_{linac}}$

Arrival Time Jitter: Model Validation

Courtesy of G. Giannetti, supervised by M. Bellaveglia and L. Piersanti

- Four working points have been considered: On Crest (**OC**, maximum beam energy), Velocity Bunching at maximum compression (**VB**, minimum bunch length), Velocity Bunching 3 and 6 degrees toward the crest (**VB3**, and **VB6**)
- Comparison for c_i coefficients, simulated and measured by RFD and EOS:

	OC		VB			VB3			VB6		
	Meas. RFD	Sim.	Meas. RFD	Meas. EOS	Sim.	Meas. RFD	Meas. EOS	Sim.	Meas. RFD	Meas. EOS	Sim.
c_1	**0.72**±0.08	0.63	**-0.09**±0.12	**-0.16**±0.05	-0.10	**0.03**±0.10	**0.04**±0.06	0.01	**0.05**±0.10	**0.12**±0.05	0.11
c_2	**0.17**±0.07	0.37	**-0.12**±0.11	**-0.03**±0.08	-0.04	**0.01**±0.08	**0.04**±0.05	0.02	**-0.04**±0.09	**0.02**±0.04	0.08
c_3	**-0.05**±0.07	0.00	**1.15**±0.10	**1.14**±0.06	1.14	**1.04**±0.11	**1.00**±0.07	0.97	**0.83**±0.10	**0.86**±0.06	0.81
c_4	-	0.00	-	-	0.00	-	-	0.00	-	-	0.00
$\sum_{i=1}^{4} c_i$	**0.84**±0.22	1.00	**0.94**±0.33	**0.95**±0.19	1.00	**1.08**±0.29	**1.08**±0.18	1.00	**0.84**±0.29	**1.00**±0.15	1.00

- Good agreement between experimental data and simulations: the proposed model is validated
- The slight disagreement for OC requires further investigations
- Coefficient c_4 is negligible for all working points
- For OC, the photo-cathode laser and klystron 1 play the most important role
- For VB, VB3, and VB6, klystron 2 is practically the only source impacting on the beam arrival time.

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Timing System

Courtesy of A. Stella

- Technical System for generation and distribution of **bunch rep frequency (100 Hz)** signals (RF synchronized) with appropriate delays to coordinate the sequence of events for beam generation & transport and trigger instrumentation
- **General requirement and major technical specifications** have been **identified**, in collaboration with WP15 - WP16 , to implement a system based on commercial HW, adaptable to Eupraxia scale and capable **to provide also custom bunch rep rate decimation and event tagging**
  - event tagging will be developed in parallel with WP 16 (**Control System & Interlocks**)
    - By the end of the year => quotation evaluation
- Hardware and technologies provided by different commercial vendor are being evaluated (MicroResearch, White Rabbit products , GreenField Technologies)
  - Quotations received (~30 keuro: minimal system -> Master Oscillator +1 delay unit, for lab tests and proof at SPARC_LAB)

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WP17: Magnets & PS

Courtesy of L. Sabbatini, A. Vannozzi

NEW ENTRY: Franco Di Bona, from fellow (since Sept 1st) to PhD student

first task: support to magnetic design of quads (Degree thesis on quadrupole design)

WORK IN PROGRESS:

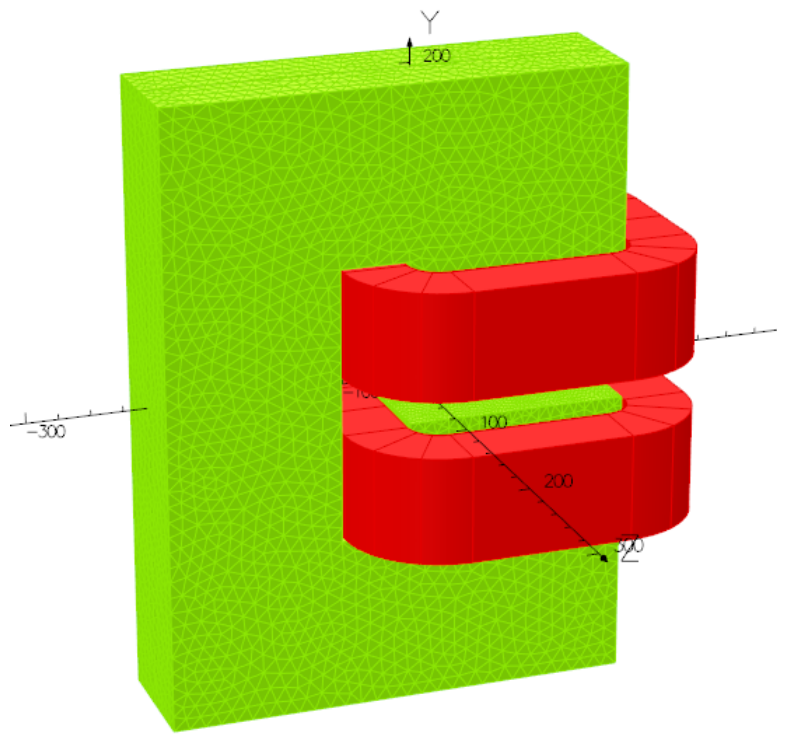
DIPOLES: magnetic design ready for:

BLH (4x laser heater chicane)

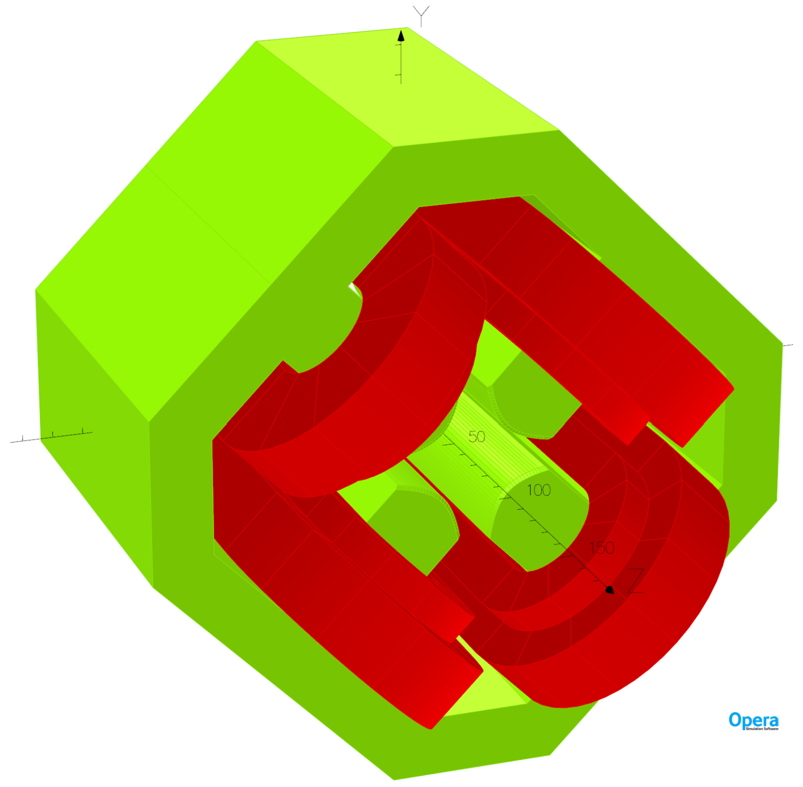
BC (4x compressor chicane)

DIPSPL (first spectrometer)

QUADRUPOLES: magnetic design ongoing for all the three families.Optimization



Control System for power supplies: first estimation of specs.



WHAT NEXT:

DIPOLES: detailed magnetic design including quality and harmonic analysis

review of magnetic design with BD by providing field maps

QUAD: focus on integrated quadrupole (the one including steering and diagnostics)

need of dedicated meetings with diagnostics and mechanics

From the last TDR Review Report

- ## Referee suggestions

  - The topology of this section is based on that of SPARC LAB, which includes a S-band gun and two S-band accelerator structures. The R&D steps and the required experimental veriFIcation of the performances at SPARC LAB are well integrated in the schedule toward the TDR. Since the new clamped RF-gun prototype has been shown to achieve the required RF parameters, this section does not appear to pose any fundamental technical risk. However, the implementation in the building requires special attention, and in particular to **provide enough space for a cathode loadlock system**. The space requirements for future upgrade (C-Band RF-gun) should be estimated before fixing the bunker design. Since the transverse homogeneity of the UV laser on the photo-cathode is probably the main ingredient for achieving very low normalized slice emittances (0.2- 0.5 mm.mrad), **the RC suggests considering a substantial laser energy reserve to allow for energy-hungry shaping techniques**. **Semiconductor cathodes could help relaxing the laser parameters requirements**.

- **Load lock system**: R&D is foreseen (in collaboration with other labs) to reduce the longitudinal extension
- **Laser energy reserve**: A plan to work with 400 nm is under study => feasibility studies started at SPARC_LAB, preliminary results shown
- **Semiconductor cathodes**: They seem to be not suitable mainly for two reasons: slow temporal response and limited peak field on the cathode

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R&D Financial Requests

Tab.4: *Detailed list of equipment to be procured*

Working Area	Family items	Year	Amount (k€)	Note
1 - Beam Physics	Computing cluster	2021	250	Needed for full 3D Simulations
2 – Injector	Upgrade Photocathode laser	2021	725	Laser+room cond.+UV optics, crystals, gratings, homogenizer
	Upgrade LLRF	2021	100	2 S-band LLRF (~160k)
	Upgrade Synch System	2021	100	New OMO, 2 Optical to electrical converter, Install. from company and commissioning
	Timing system upgrade	2021	50	Prototype of the new timing system
	RF Gun prototype for high rep rate	2022	25	Mechanical design, thermal sim. with cool cathode
	S-Band modulator	2022	550	S-band solid state mod + cabling -> time scale ~ 1.5y (from the order)

Conclusions

- The EuPRAXIA@SPARC_LAB photo injector up to the end of the S-band linac is equivalent to the SPARC photo injector
  - R&D can be done at SPARC_LAB to produce the nominal beam parameters at low energy and satisfy the stability and reproducibility requirements needed for EuPRAXIA@SPARC_LAB, for instance
    - jitter studies
    - experimental tests of the photo injector working points
    - laser pulse shaping
    - control system testing
    - plants upgrade
    - AOB

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