First TDR Review Committee Meeting
Zoom, February 22nd, 2021

WA2 - Injector
Status Report

E. Chiadroni
(INFN - LNF)
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)
  - WP13: **Beam Diagnostics** (Cianchi)
  - 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

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

July 2021: 3D CAD Design of the **photo injector layout and laser transport line**

Dec. 2021: **Simulation studies** on main WoPs

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

- **Layout** is going to be defined, being **optimized for both working points**, i.e. high charge (200 pC) no plasma and comb with plasma

Courtesy of L. Pellegrino

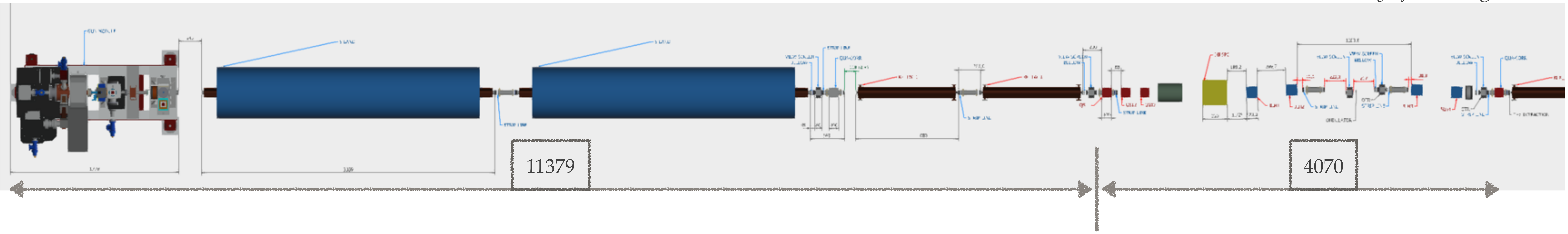


Photo injector layout update

- SABINA photoinjector up to the end of the 2 S-band TW accelerating structures
- X-band linac layout up to the laser heater inserted in the TStep model

Benchmark with different codes

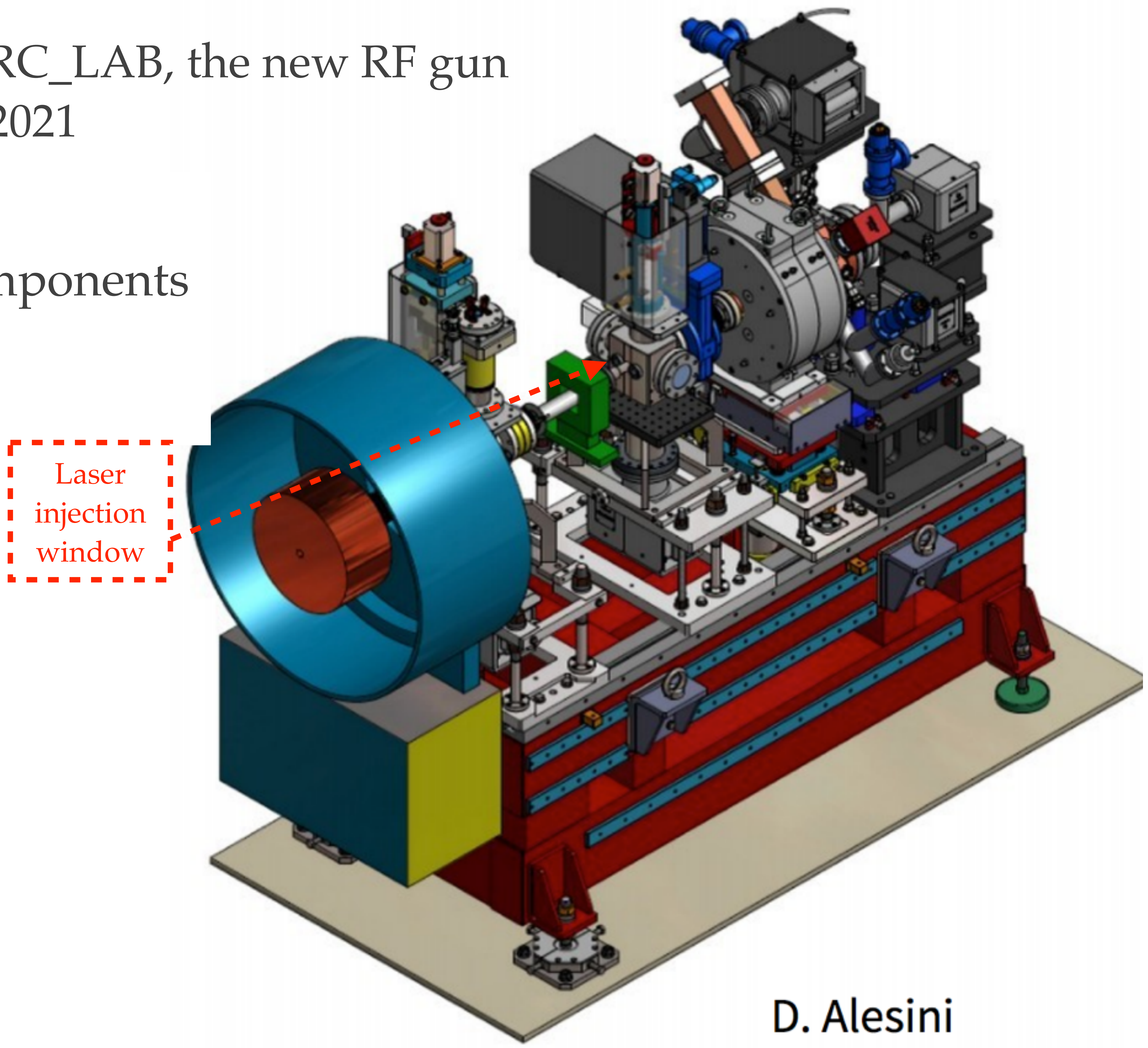
The machine model has been implemented in ASTRA

- High charge WP cross-checked

SPARC_LAB RF Gun upgrade

- In the frame work of SABINA project at SPARC_LAB, the new RF gun will be installed and commissioned in April 2021

The upgrade takes into account
- compensation of the quadrupoles components
- better pumping
- external injection of the laser



D. Alesini

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S-band RF Power Station

Courtesy of F. Cardelli

- 2 RF power stations to feed the S-band gun and the two S-band linac sections
- 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
- New calculations for the power attenuation for the current layout (S band waveguides and modules of 4 sections at "low energy" and "high energy" in X band)
    - **Need to have a "quasi-final" version of the layout to project the power supply system for the 2 X-band after the S-band sections (power and phase requests)**

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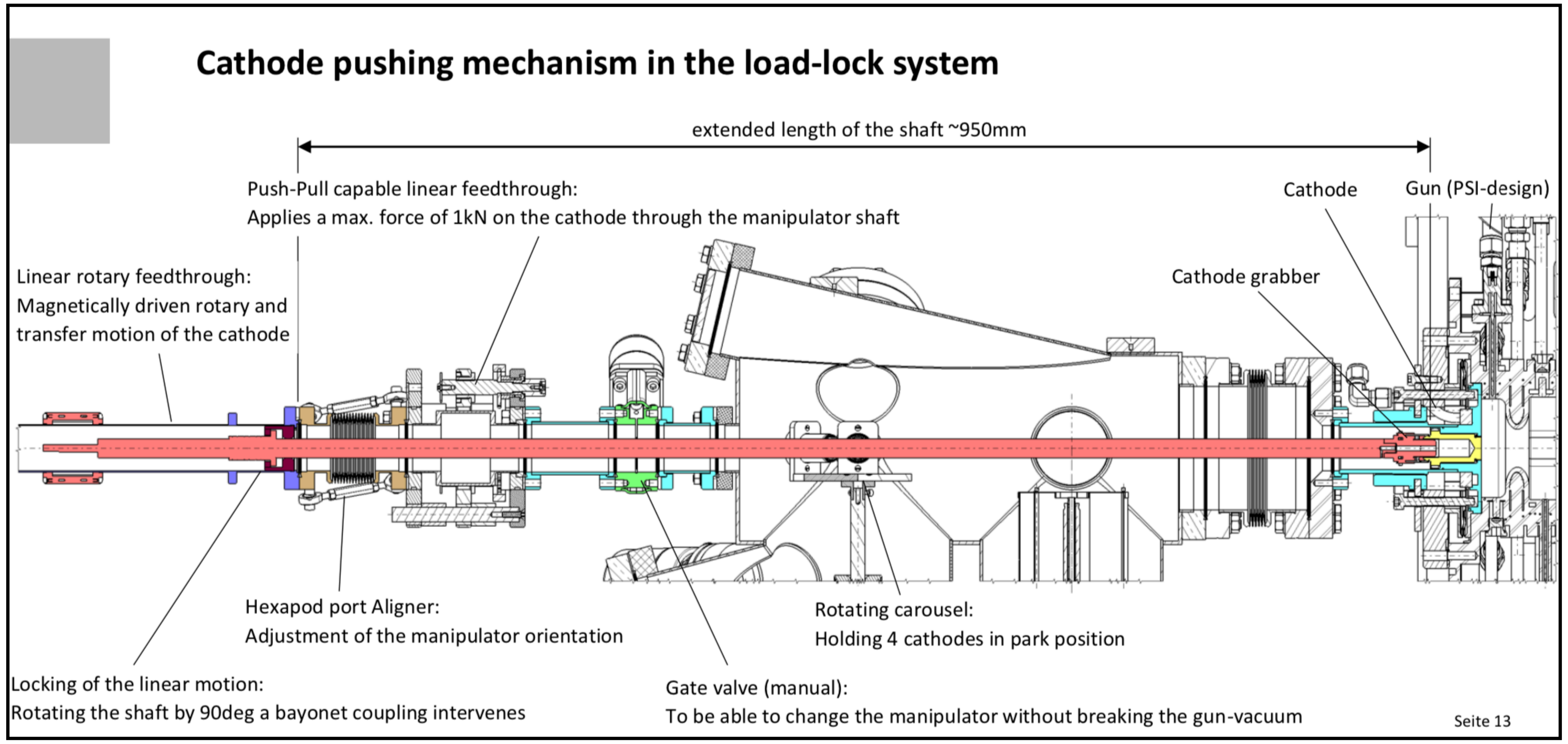
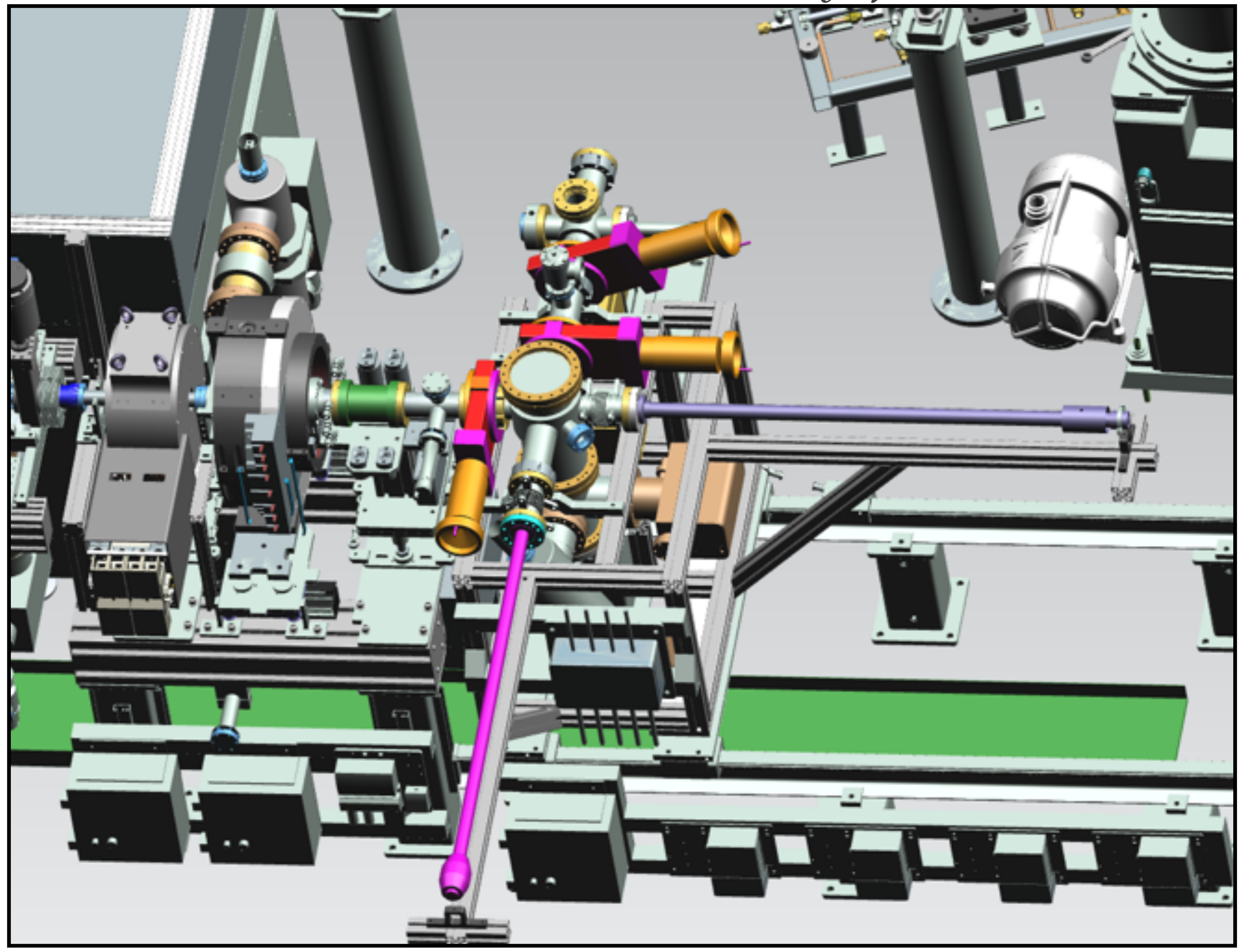
Photocathode technology

- **Phase 0** foresees a **Cu cathode** since, following Referees' recommendations, *"The electron source of an FEL user facility together with the photo-cathode laser system plays a decisive role with respect to the achievable performances and reliability of the machine. A robust design of the overall system is therefore mandatory to minimize the operational risks."*
- However, **R&D activity on novel cathodes** is undergoing at SPARC_LAB, therefore we are studying the possibility to implement a load-lock system: the main issue is now due to the lack of space behind the gun (~ 1.5 m needed)
  - Contacts with several labs (PSI, DESY, Fermi@Elettra)



Courtesy of R. Ganter and A. Zandonella (PSI)

Courtesy of F. Burkart (DESY)



Semiconducting cathodes

Courtesy of J. Scifo

- Evaluation of advantages and impact of semiconducting cathodes on beam dynamics (J.Scifo - A. Giribono)
- Cathode and laser parameter choice
  - The cathode choice implies some constraints for the beam dynamics. Among others, the laser pulse shaping and electromagnetic fields in the gun and cavities have to be properly set
    - For example for Cs_2Te cathodes

	Cs_2Te
Robustness	x
High RF gradient	No test to date! (max E_{RF} ≃ 100MV/m peak)[2]
High Rep. Rate	No test to date!(max Rep. rate=100 Hz)[2]
Laser wavelength (nm)	UV range (262-266nm)
Response time	400 fs[1]
Microbunching instability[2]	✓
Load lock system	✓
Vacuum level (mbar)	∽10^{-10} – 10^{-11}
Lifetime	Few month- few years

Maximum RF peak fields in gun and cavities

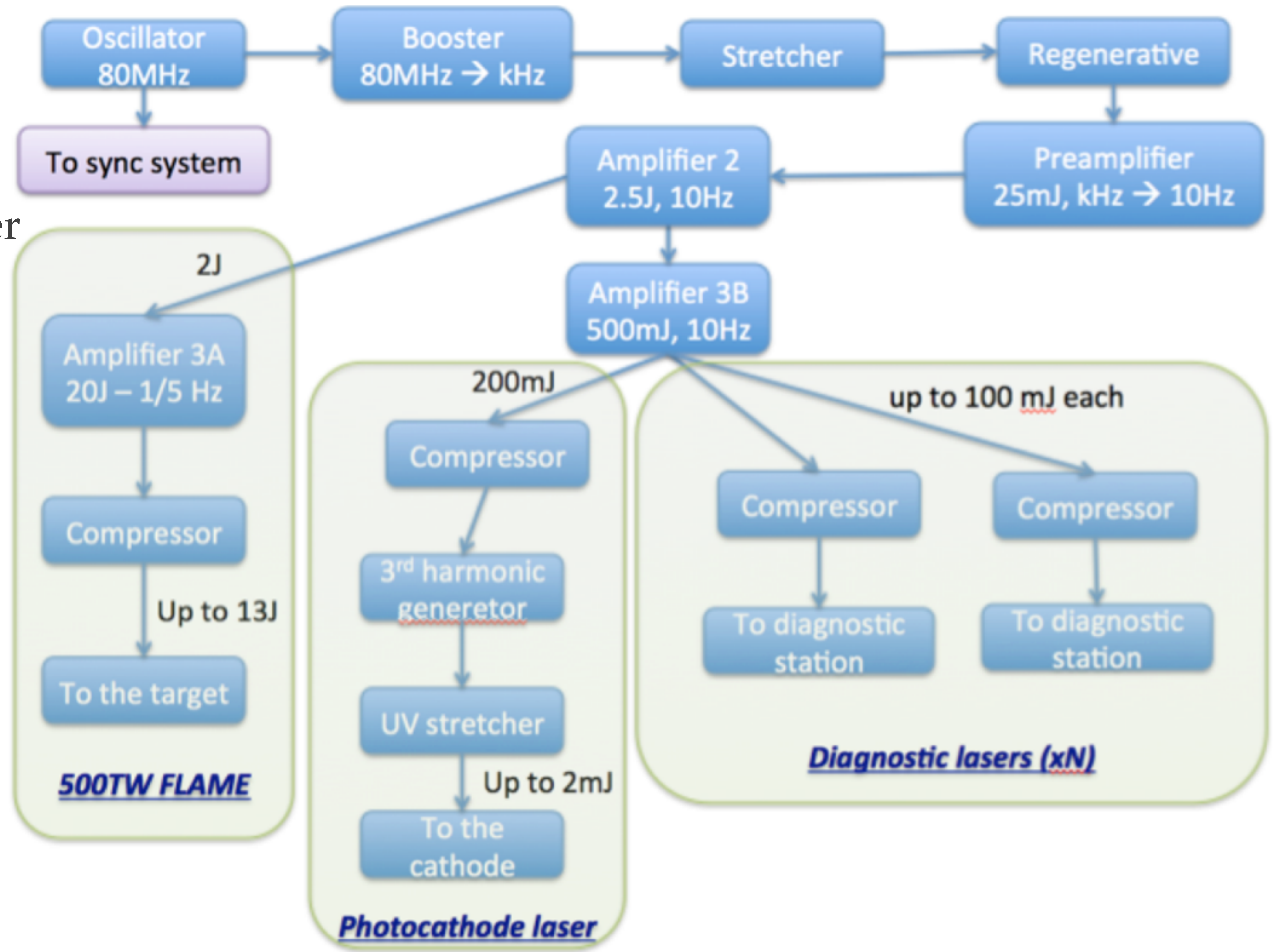
Laser pulse rising and length

1. Aryshev, A., et al. "Femtosecond response time measurements of a Cs 2 Te photocathode." *Applied Physics Letters* 111.3 (2017): 033508
2. P. Craievich: Overview of SwissFel injector design and performances, XLS meeting, November 2019, Frascati

Laser System

Courtesy of M. P. Anania

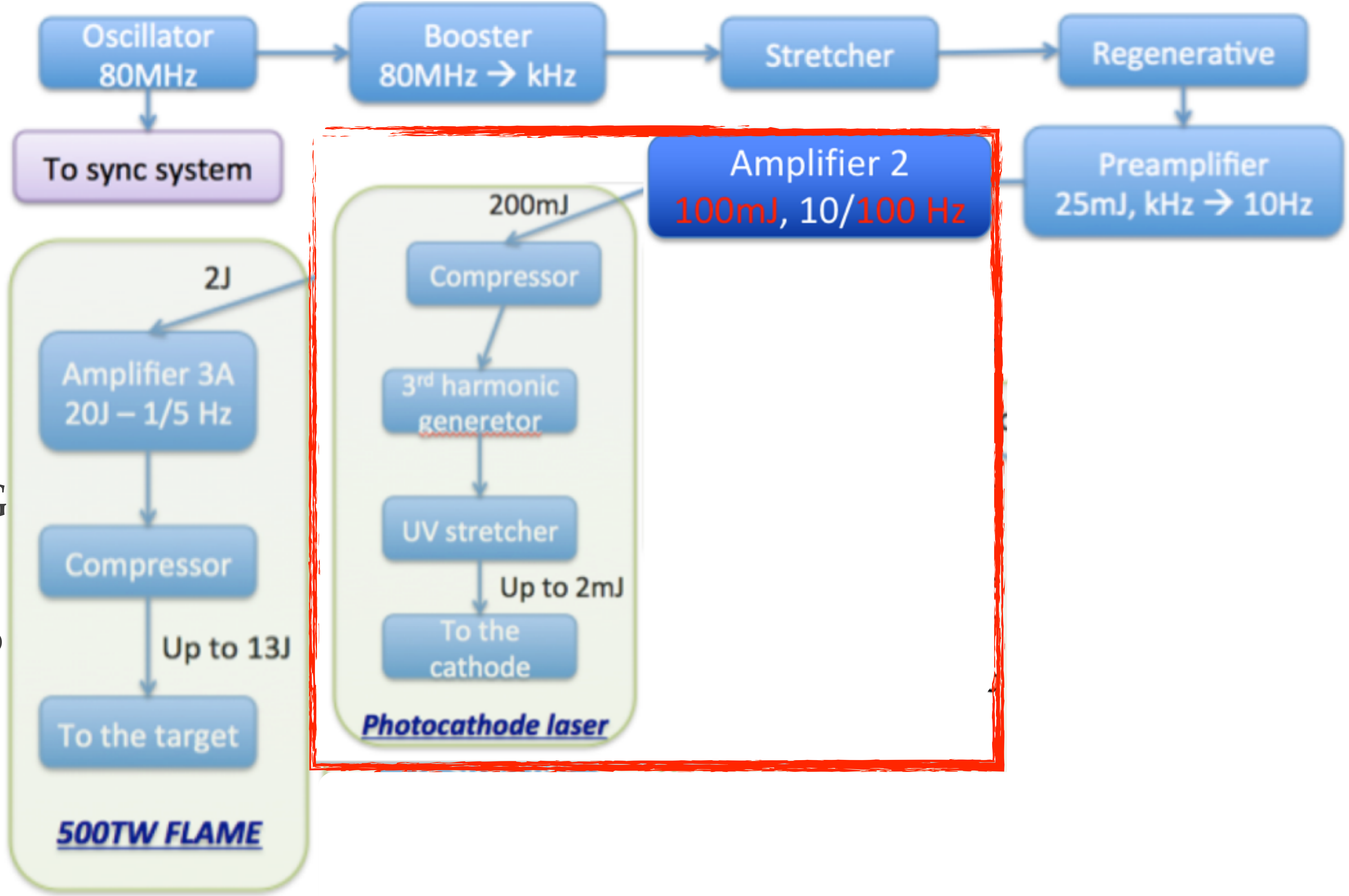
- CDR scheme of the laser systems
  - The photo-cathode laser shares the same front-end of the upgraded high power laser Ti:Sa Laser technology



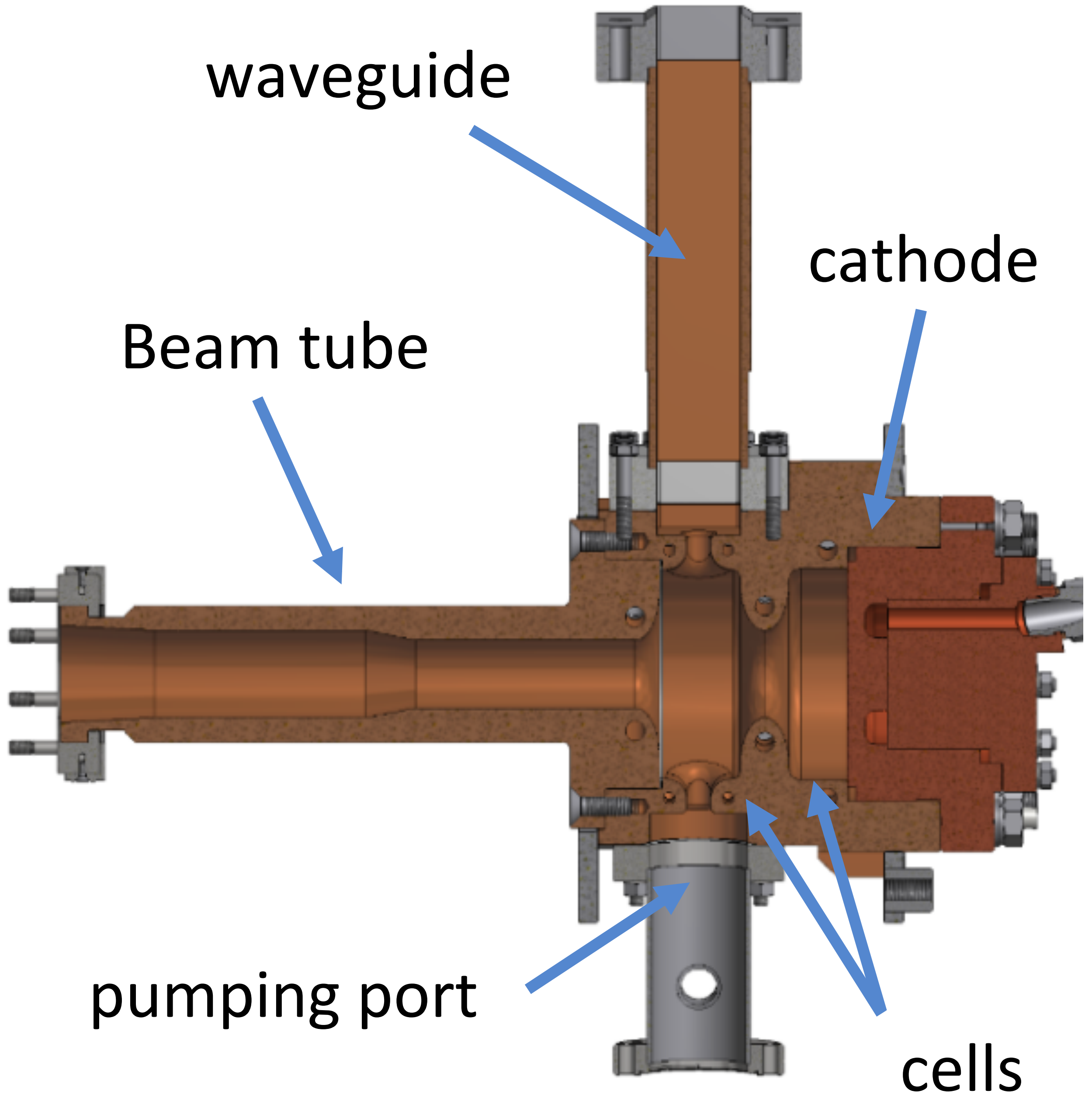
Laser System

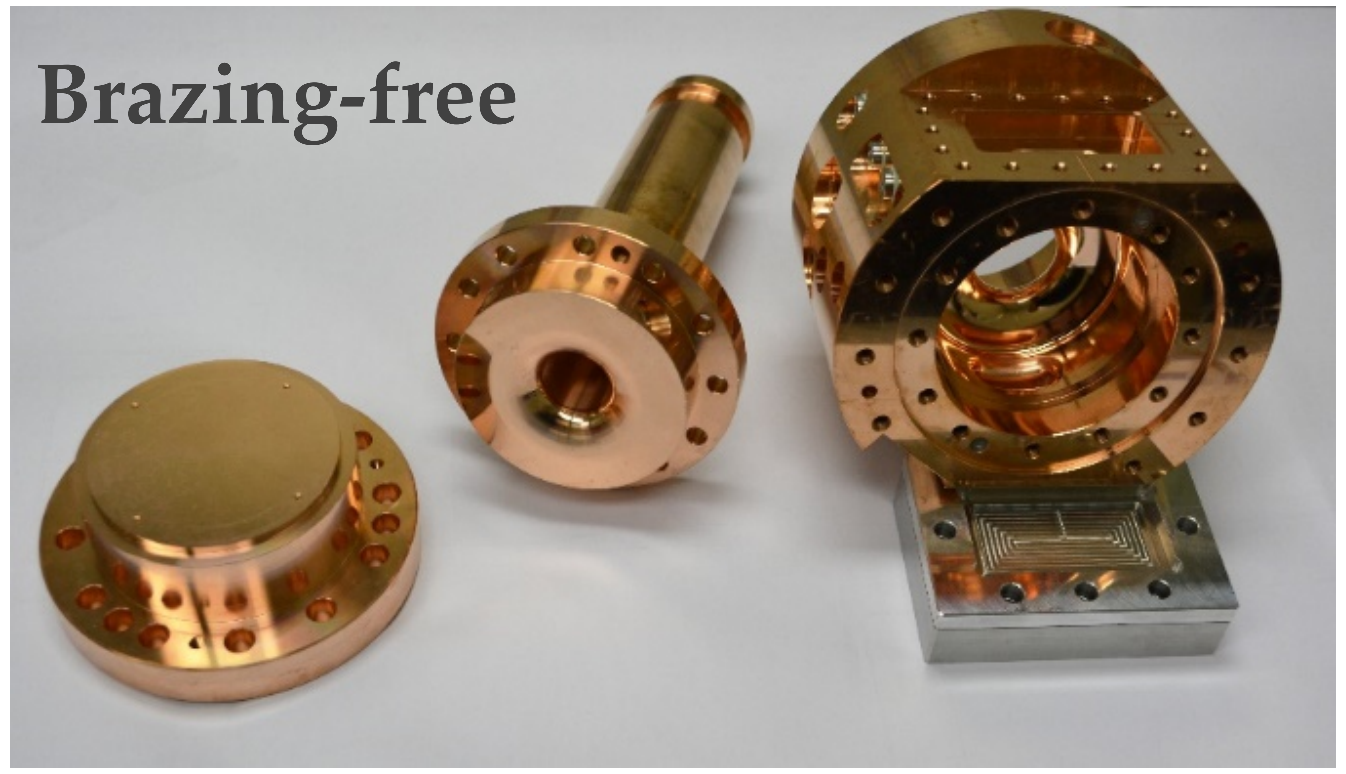
Courtesy of M. P. Anania

- Study for a possible **upgrade to 100 Hz**
  - The maximum energy available after the second amplifier must be fixed
  - 100Hz flash lamps YAG exists.
  - The preamplifier is also running at 100 Hz

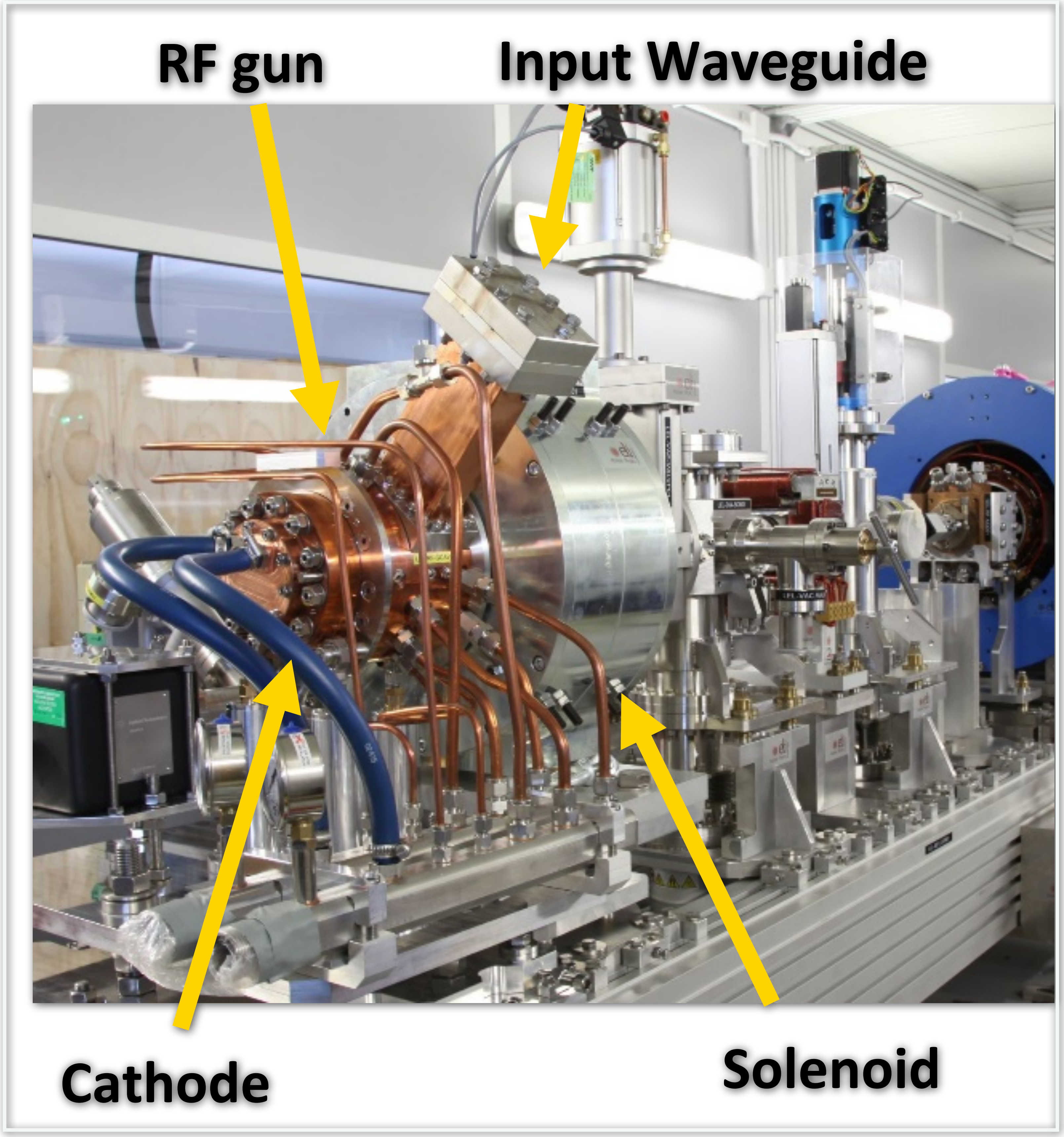


ELI-NP RF gun at 100 Hz





Courtesy of L. Piersanti



This gun has been already tested at high RF power, reaching the nominal parameters: 120 MV/m cathode peak field at 100 Hz and 1.5 μs rf pulse length

D. Alesini et al. Phys. Rev. Accel. Beams ***21****, 112001 (2018)*

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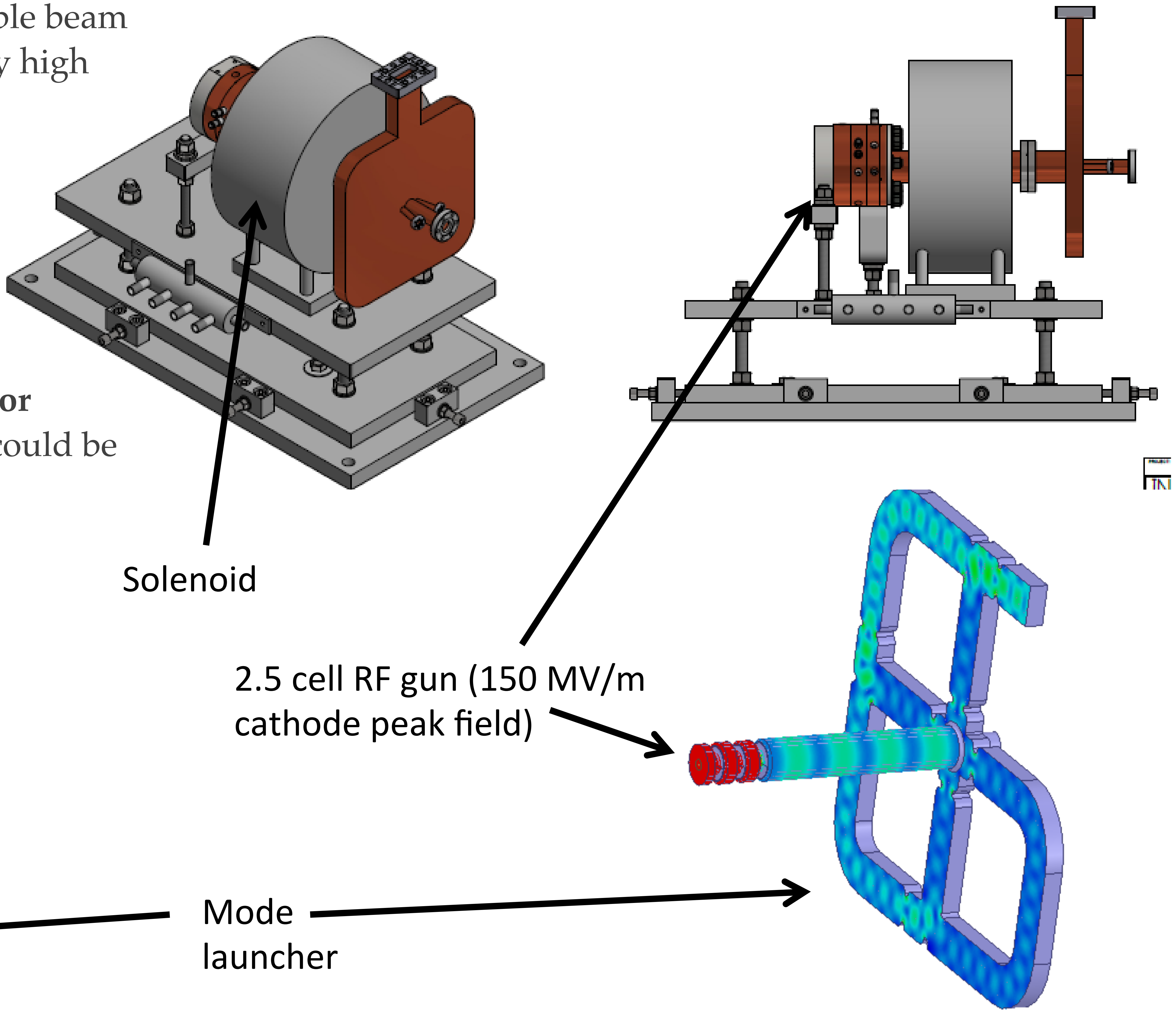
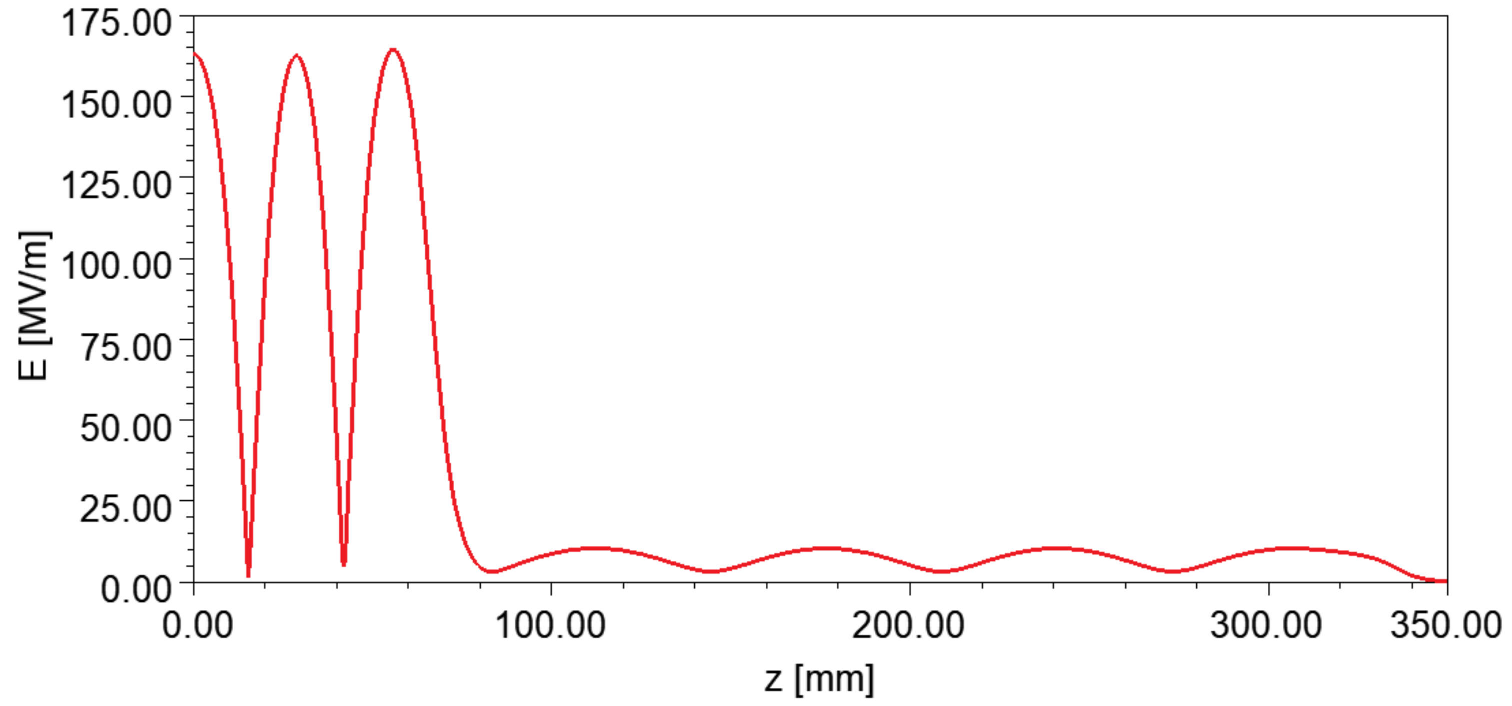
C-band RF Gun and Injector

Courtesy of D. Alesini

- An R&D activity has been started few years ago on a **C band gun and full C band injector** (gun + TW C band structures);
- Such a system **is very promising** in terms of achievable beam parameters, compactness and possibility to go at very high repetition rates (up to 1 kHz)
- This R&D program has been funded by the **IFAST (Horizon 2020) and TUAREG (INFN commission V)** projects and is oriented to fabricate and test a first prototype of a C band gun within four years.
- This system has also been selected as the **basic injector in the context of the Compact light EU project** and could be studied as a future upgrade of EuPRAXIA injector.





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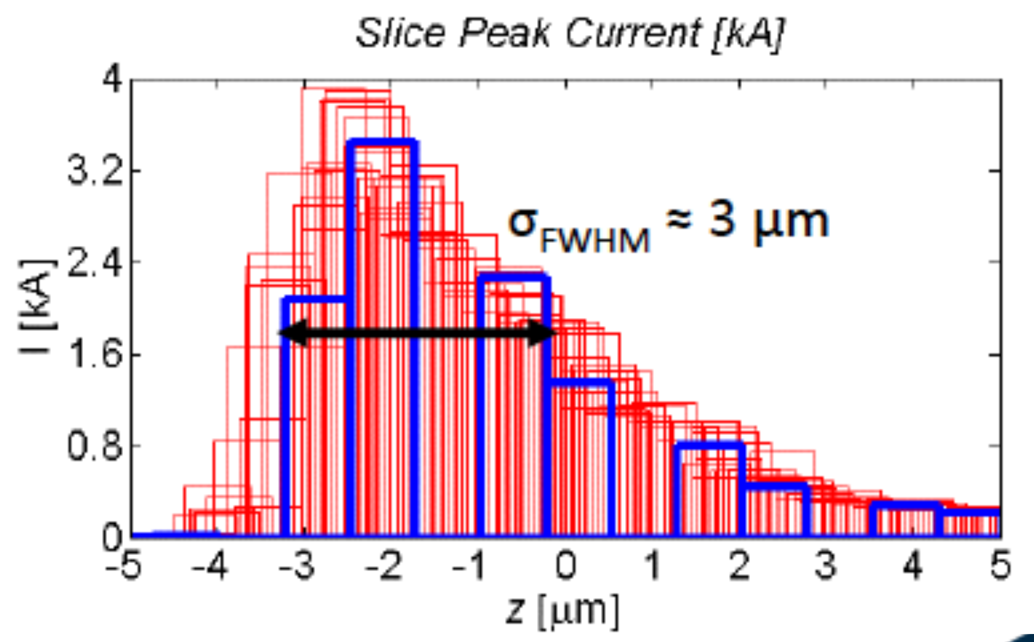
Injector Simulations

Courtesy of A. Giribono

- **Two main working points** have been identified, in particular
  1. **PWFA beam: Comb-like beam with plasma**
     - The two S-band linac sections are both operating in Velocity Bunching (RF compression)
       - *Phase jitter studies have been addressed to evaluate driver/witness time separation stability*
  2. **High charge (200 pC) without plasma (Full RF acceleration)**
     - Full studies for on-crest and RF compression scheme: *the hybrid compression is the best compromise*
       - *Sensitivity studies have been performed at low charge (30 pC) => CDR*
         - *RF phase jitter is affecting the beam length*
           - *RF phase jitter lower than 0.05 degree can ensure the needed beam peak current.*



       - *Sensitivity studies at high charge must be done*

Courtesy of A. Giribono

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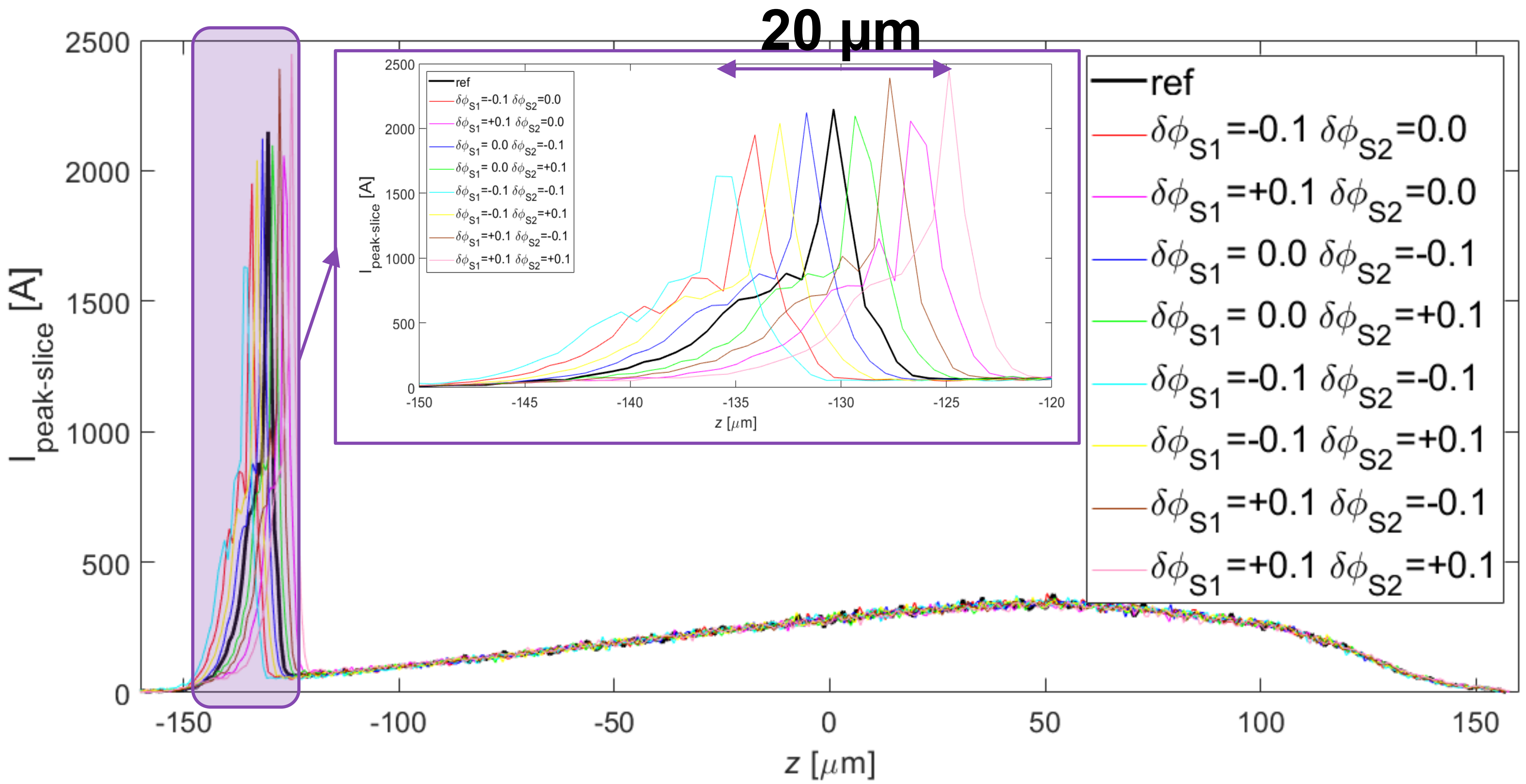
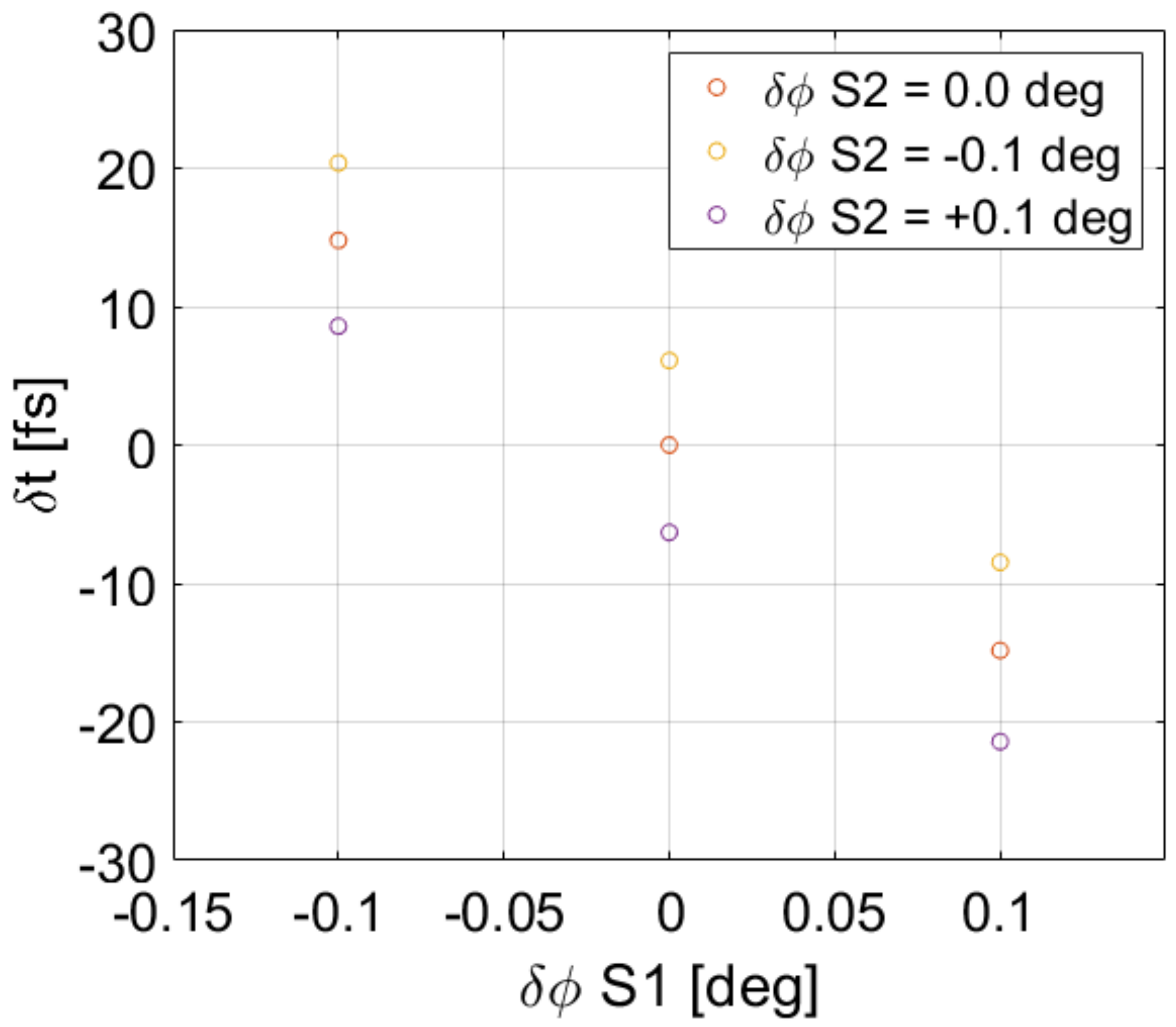
Jitters Studies

Courtesy of A. Giribono

- Jitter studies or the PWFA WoP considering a **S1 and S2 Δϕ in the range ±0.1deg**
  - **Evaluate the effect on the witness/driver time separation**
- Due to limited computing resources only the extreme values of the jitter have been simulated on **both first and second S-band cavities** operating in the **velocity bunching regime**



Longitudinal slice analyses at 2nd S-band TW structure exit for various Δϕ. The beam separation continues in the downstream linac up to the 2nd X-band TW structure



Delay between driver and witness with respect to the Δϕ = 0 deg case

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Brainstorming on Jitters

- WA1 (***Beam Physics***, *C. Vaccarezza*), WA2 (***Injector***, *E. Chiadroni*) and WA3 (***Linac***, *D. Alesini*) joint periodic meetings to study physical and technological aspects necessary to face with any kind of jitters (e.g. RF, charge, plasma density,…), which might prevent successful operation of a plasma-based (user) facility
- **Stability requirements are dictated by the final application**, e.g. SASE FEL energy stability
  - In case of **PWFA**, **RF jitters affect** not only the peak current, but also the **time separation** between driver and witness
- Focus on two cases
  1. SPARC_LAB (**high priority**)
     - At present, **what is the bottle neck**? What can we do to improve the stability?
     - **define a list of technological choices** we should afford to overcome the present limits
     - **define a list of additional components** to be replaced or purchased to improve the stability in VB operation
  2. EuPRAXIA@SPARC_LAB
     - **Outcomes from 1. are mandatory for the TDR** (time scale ~ 3 years) to validate to the choice of the comb-based PWFA and to gain experience
     - **Alternative schemes** for the driver-witness generation **must be investigated**, focusing on the stability and versatility in terms of ramp particle distributions
       - **Warning**: Schemes foreseeing masks need high bunch charge => check compatibility with laser and cathode technology

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     Dedicated talk by M. Bellaveglia this afternoon
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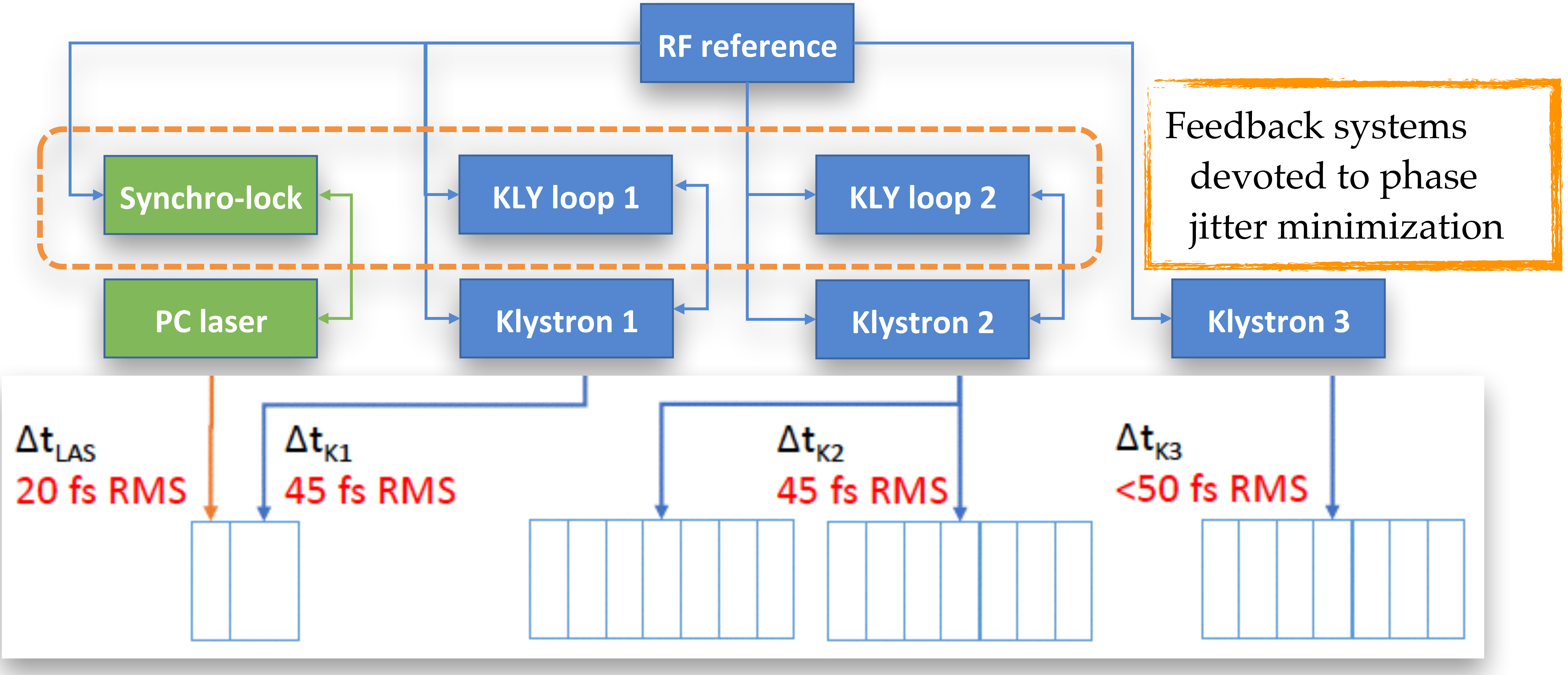
Different type jitters

Courtesy of L. Piersanti/M. Bellaveglia

- **RF power plants/PC laser vs RF reference**
  - Quality of the fast phase-lock of the sub-systems to the RF reference



- **Electron beam Arrival Time Jitter (ATJ)**
  - Quantifies the beam stability in time at a certain point of interest
  - It is relative to the system performing the measurement
  - Its value is **strongly affected by the machine working point** (Velocity Bunching or Crest)

Arrival Time Jitter

Courtesy of L. Piersanti

- The ATJ is produced by several sources, e.g.
  - changing of the laser arrival time on the PC, Δt_{laser}
  - instabilities in the timing of the RF system, Δt_{RF}
  - instabilities fluctuations in the amplitude of RF and magnetic fields of dispersive elements

Three main sources:
PC laser and two S-band klystrons:
Kly1 feeding gun and RFD, while Kly2 powers S1 and S2

$$\Delta t_{linac} \approx \sum_{i=1}^{3} c_i \Delta t_i$$

If the laser and RF fields are delayed all together by a given value, the beam arrival time is delayed by the same amount

$$\sum_{i=1}^{3} c_i = 1$$

All Δt_i values are measured with respect to the reference. Since they are mostly uncorrelated

$$\sigma^2_{t_{linac}} \approx \sum_{i=1}^{3} c_i^2 \sigma^2_{t_i}$$

representing the expected **absolute ATJ** (with respect to the reference) **at the linac exit**.

Different type jitters

Courtesy of L. Piersanti

- At SPARC_LAB we measure the beam ATJ with 2 diagnostics systems: RFD (beam vs K1) and EOS (beam vs PC-laser)

$$\sigma_{t\,RFD} = \sqrt{C_1^2\sigma_{las}^2 + (C_2-1)^2\sigma_{K1}^2 + C_3^2\sigma_{K2}^2}$$

On crest working point

$$\sigma_{t\,EOS} = \sqrt{(C_1-1)^2\sigma_{las}^2 + C_2^2\sigma_{K1}^2 + C_3^2\sigma_{K2}^2}$$

Velocity bunching working point

	C1	C2	C3
CREST	0.7	0.3	≈0
VB	≈0	≈0	≈1
VB over compression	<0	<0	>1

R. Pompili et al 2016 New J. Phys.18 083033

Using a reasonable «guess» on the jitter actual values

Working point	C1	C2	C3	σ_{las} (fs)	σ_{K1} (fs)	σ_{K2} (fs)	RFD est. (fs)	RFD meas (fs)	EOS est. (fs)	EOS meas. (fs)
ON CREST	0,7	0,3	0	20	45	45	34,5	35,1	14,8	N/A
VB (over-compr.)	-0,05	-0,05	1,1	20	45	45	68,4	75	53,8	51

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Synchronization system upgrade

Courtesy of L. Piersanti

- KLY loop upgrade (new phase shifters, new err. amp) -> K1-K2 vs RF expected small contribution to jitter performance
- Optical synchronization system -> PC-laser vs RF jitter performance
  - Complete redesign of RF reference distribution PC-laser lock and power plant feedback systems
  - Paramount importance in view of EuPRAXIA at SPARC_LAB
- **Brand new digital LLRF system** -> sensitivity
  - RF front-end higher resolution
  - Higher pulse stability
  - Possibility to arbitrarily shape the RF pulse (amplitude and phase)

SABINA

Synchronization system upgrade

Courtesy of M. Bellaveglia

- At SPARC_LAB we are using PFN to generate HV needed by klystrons
  - The added jitter of hundreds of fs RMS is reduced to tens of fs RMS using fast phase loops
- To further reduce **K1-K2 vs RF jitter**, one way could be to change modulator technology (from PFN to solid state) => **S-band solid state modulator (EuPRAXIA@SPARC_LAB)**
  - The klystron added jitter will be reduced at best **<20 fs RMS** (measured in facilities already running)
    - **This level is still not suitable for the plasma-based accelerator requirements**
      - Study the **upgrade and use of the klystron loops also around solid state supplied klystron**
        - tests using solid state C-band modulator at SPARC_LAB are feasible

Timing System

Courtesy of A. Stella

- Technical System for generation and distribution of **bunch rep frequency** 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**
- A **survey** of existing systems in other laboratories has been carried on
- Hardware and technologies provided by different commercial vendor are being evaluated (MicroResearch, White Rabbit products , GreenField Technologies)

WP16: Control System & Interlocks

Courtesy of A. Stecchi

- **Undergoing activity**
  - Course on Jira to encourage people to work with a modern project tracking tool and follow agile development methodologies
  - Collaboration with the Project Manager for the creation (outsourced) of a document management system
  - A complete and in-depth analysis of the various control frameworks is underway => course on the Tango Control System
  - Upgrade of the FLAME control using the !CHAOS framework
- **Foreseen activity**
  - Collect specifications for
    - timing, synchronization, # of channels, readout frequency, bandwidth, correlation with other systems
    - user applications: control panels, general features, high level applications
    - data storage and retrieval, interface with user data analysis tools (eg. ROOT, Mathematica, MathLab, etc …).
  - Continue the analysis of the candidate frameworks for the control of EuPRAXIA, i.e. EPICS and !CHAOS
  - Final decision on which control framework to adopt (as a result of the above analysis)
    - IF an external framework will be adopted → Drafting of technical specs for the outsourcing of the chosen system
    - IF !CHAOS will be adopted → Start of control in-house implementation
  - Evaluation of hardware needs (as a result of the above analysis & collections of specifications)

Dedicated talk by A. Stecchi this afternoon

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WP17: Magnets & PS

Courtesy of L. Sabbatini

- Joining WA and layout meetings
- Identification of *magnets families*
- Photoinjector: SABINA-like frozen design
- Dipoles: preliminary magnetic design of BLH family (laser heater chicane)
  - Undulator Laser Heater is a WP18 duty
- Dipoles: preliminary magnetic design of DIPSPC (spectrometer)
- Quadrupoles: magnetic preliminary design of QS triplet (300MeV)

By April 2021

- detailed design of all dipoles and quadrupoles
- evaluation of power supplies (also on the basis of plant constraints, i.e. distance between magnets & ps)

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