III TDR Review Committee Meeting
Frascati, June 06th, 2022

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)
  - 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: ***Laser studies for high rep rate operation***

June 2022: *X-band linearizing cavity design study*

July 2022: *Finalization of simulation studies*

Dec. 2022

Mar. 2023: *Project of the* ***photocathode laser***

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

June 2023: ***Laser Heater*** *project*

Beginning of 2025: ***TDR completion***

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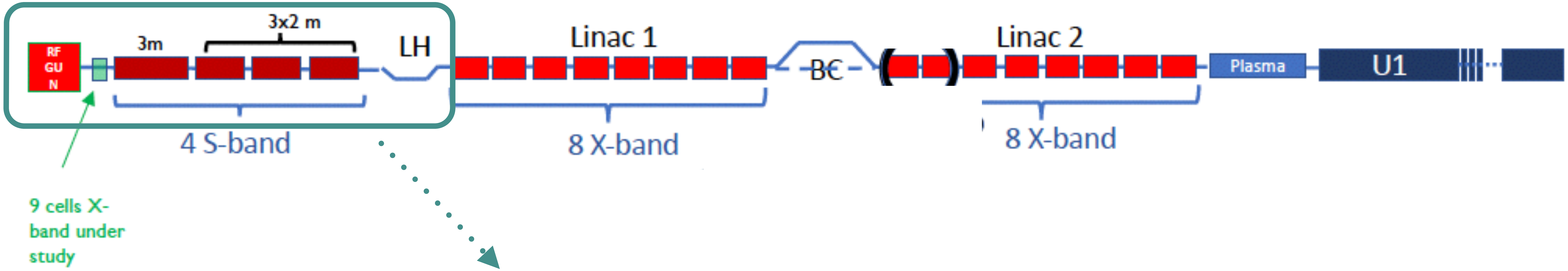
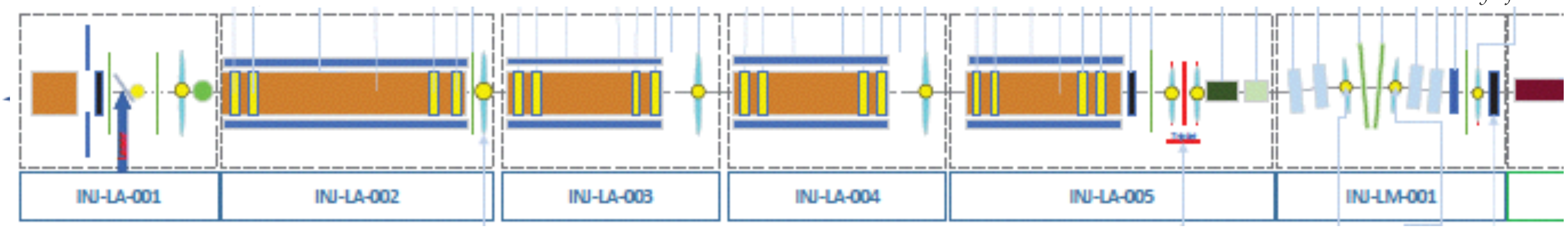
Current injector layout





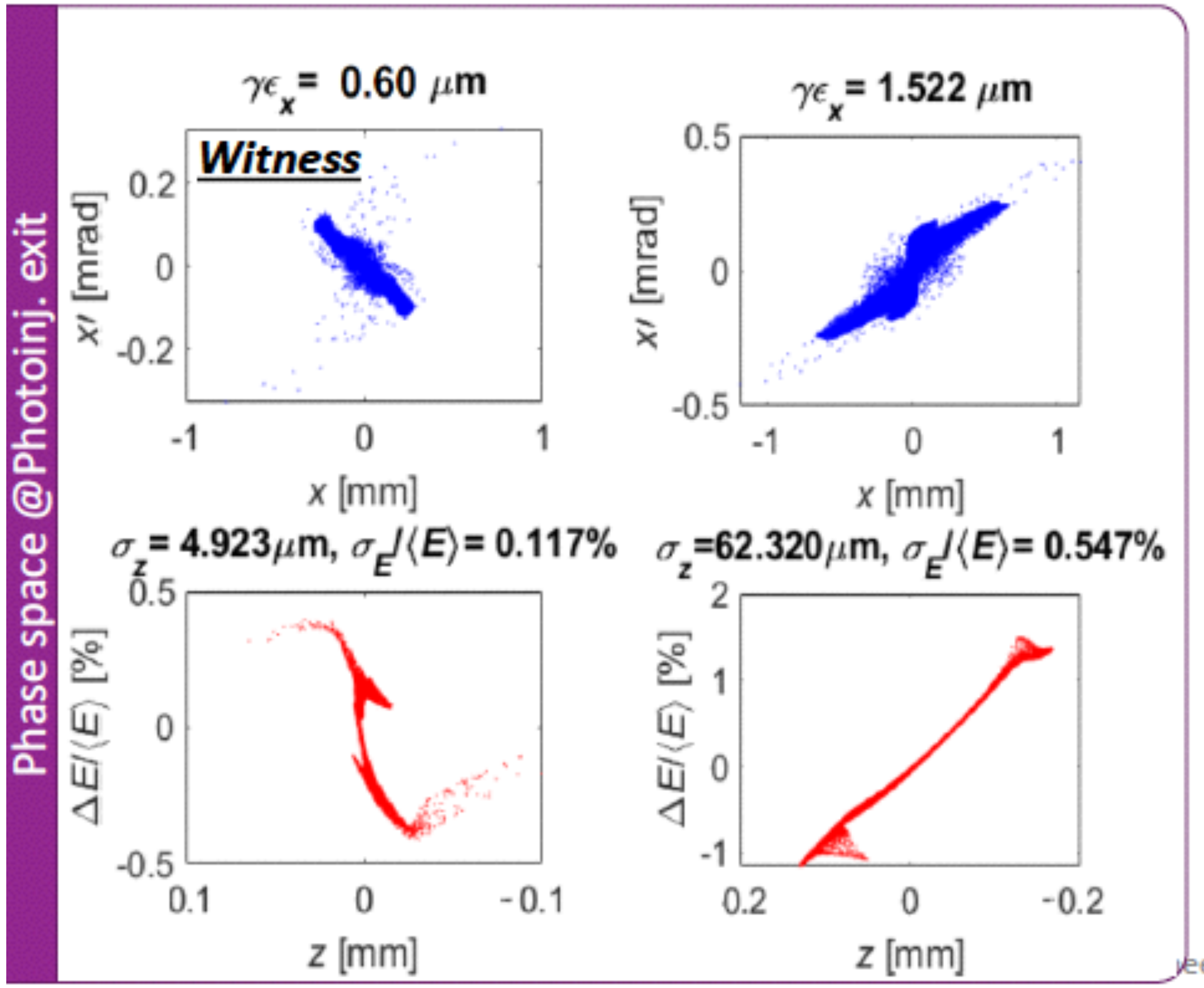
Courtesy of F. Cioeta

- Design study of a new photo injector consisting of four S-band accelerating structures plus an X band cavity placed right after the gun
- The new baseline foresees a photo injector composed of the S-band RF gun followed by a 3 m long S band structure and three 2 m long ones

Injector Simulations

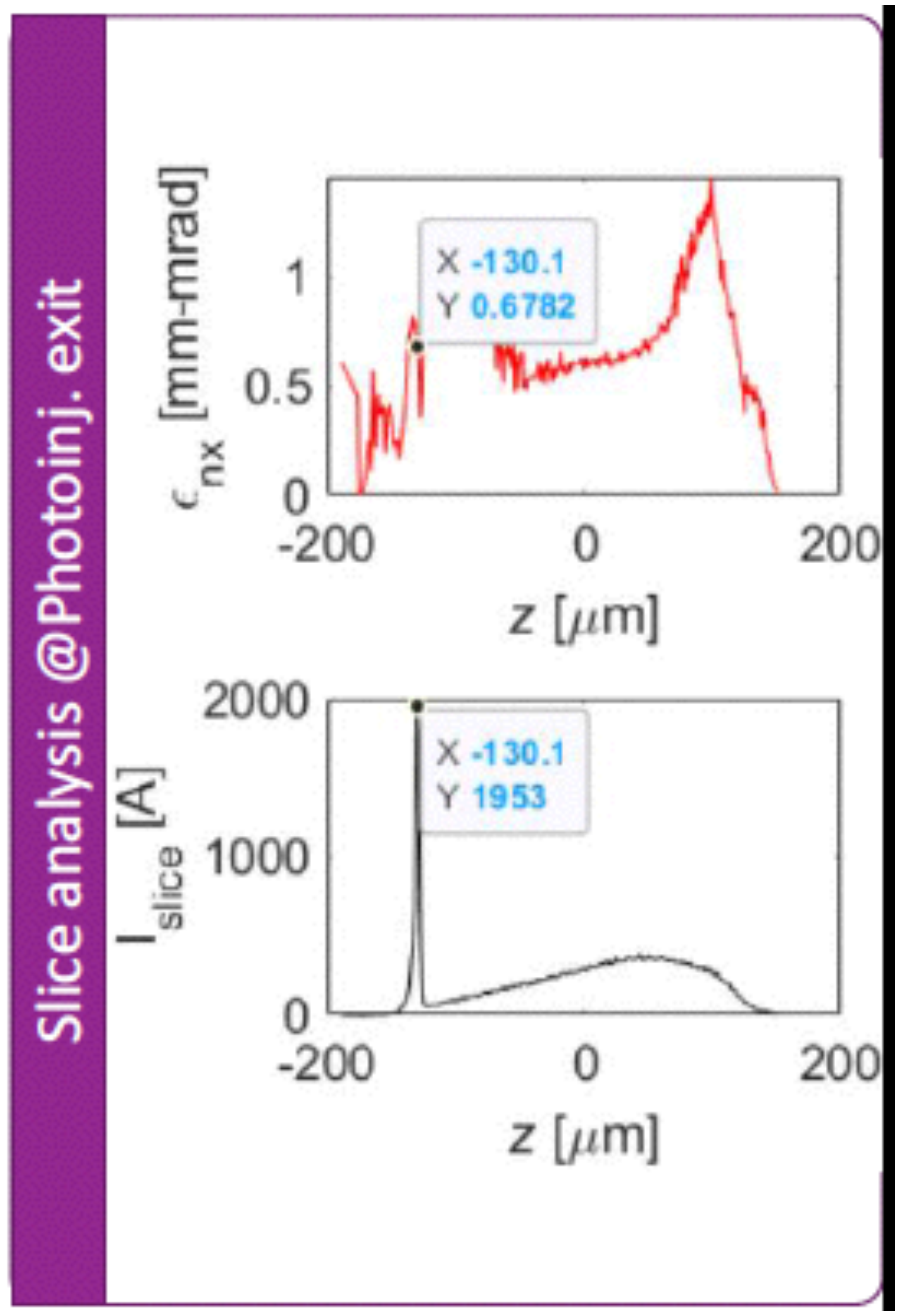
Courtesy of A. Giribono

- The beam dynamics has been studied varying the photo-injector setup so to explore a wide range of tunability in terms of witness-driver delays and witness peak current



Beam parameters @Photoinj exit		
	Witness	Driver
E [MeV]	124.75	126.46
$\varepsilon_{x,y}$ [mm mrad]	0.60	1.52
$\sigma_{z\text{-rms}}$ [µm]	4.923	62.320
ΔE/E [%]	0.117	0.547
Δt [µm] (ps)	151.5 (0.505)	
$\sigma_{x\text{-rms}}$ [µm]	118	127
$\beta_{x,y}$ [mm]	6.127	2.609
$\alpha_{x,y}$	2.475	-1.534

eeting May'22 - A.Giribono



Courtesy of A. Giribono

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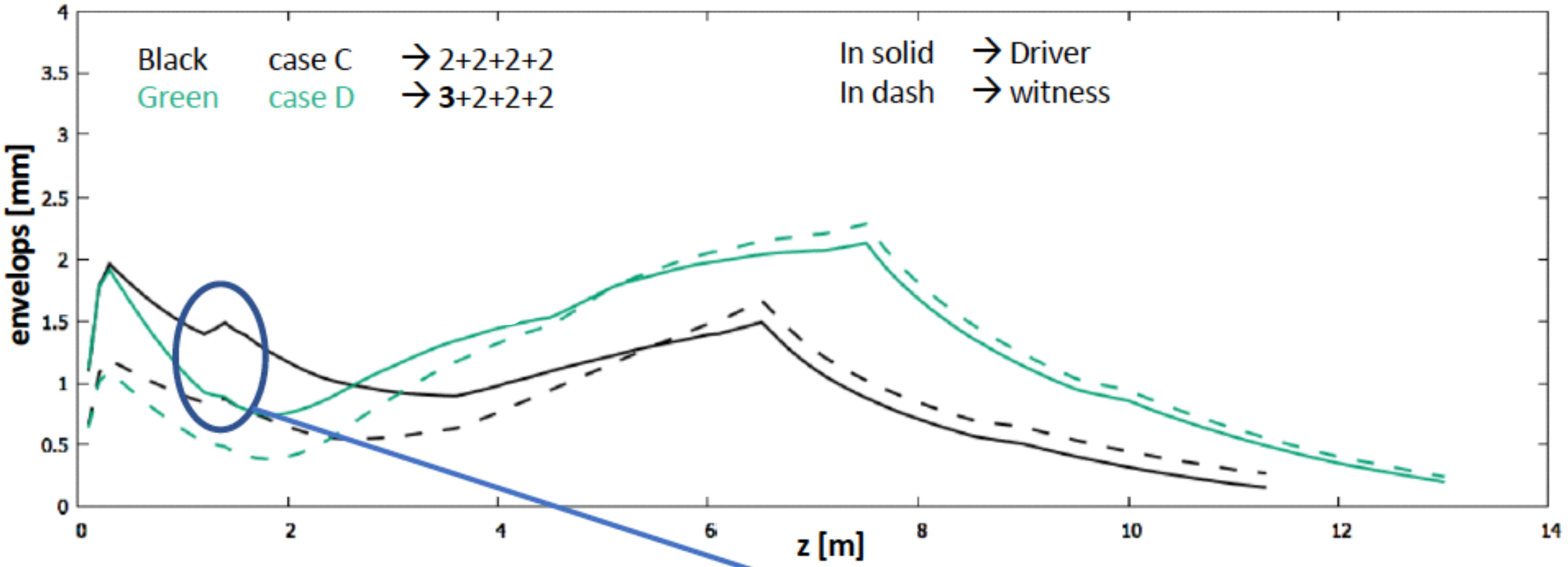
Injector Simulations

Courtesy of A. Bacci

- The study on the X-band cavity after the gun has been addressed with good results and then embedded in the layout



It evident the defocusing effect of the X-band

CASE C – has a dynamic with larger envelops @ X-band – anyway the whole bunch passes the irises
CASE D – much better to host the X-band

X-band Linearizer

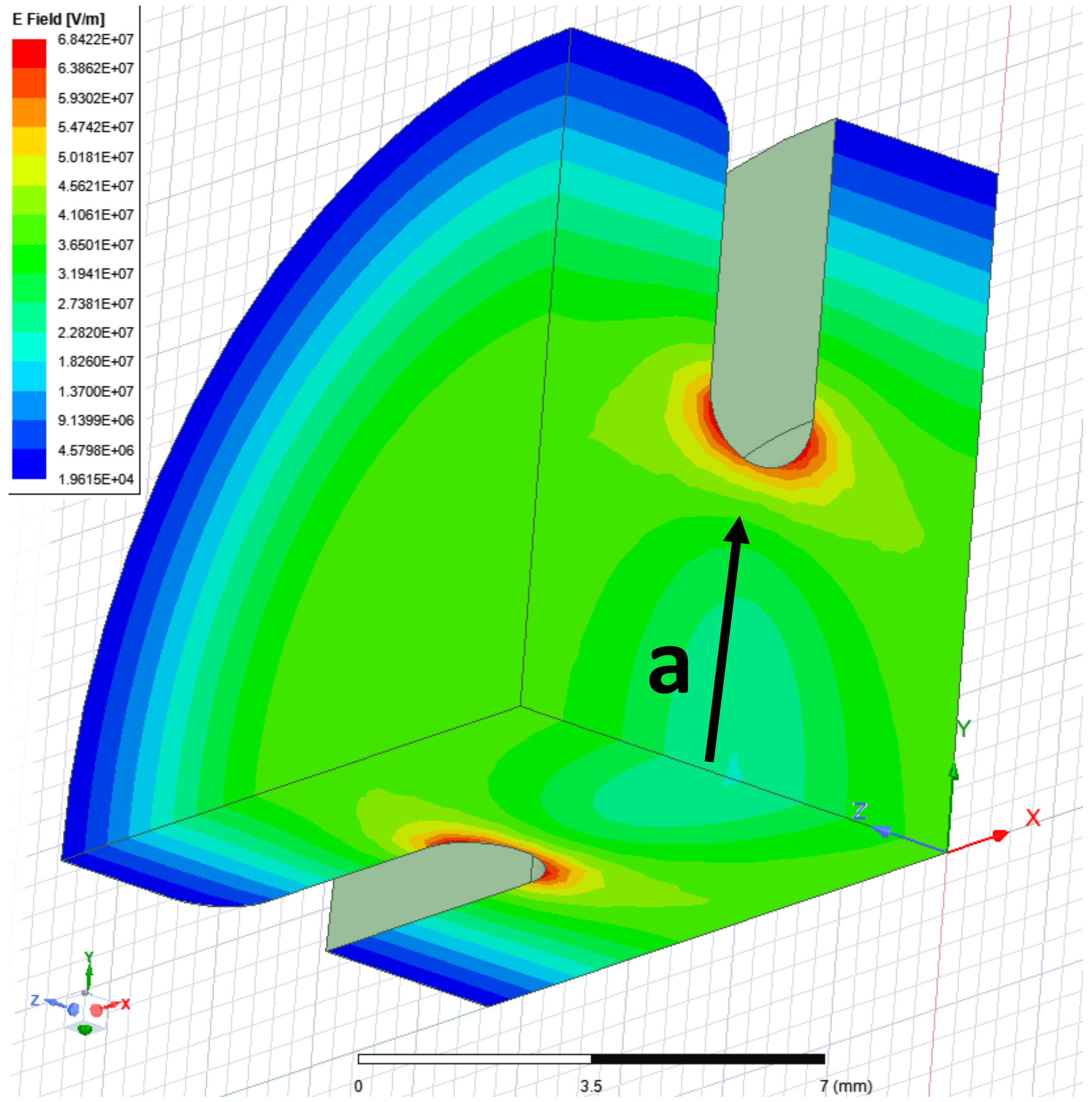
Requirements from Beam Dynamics

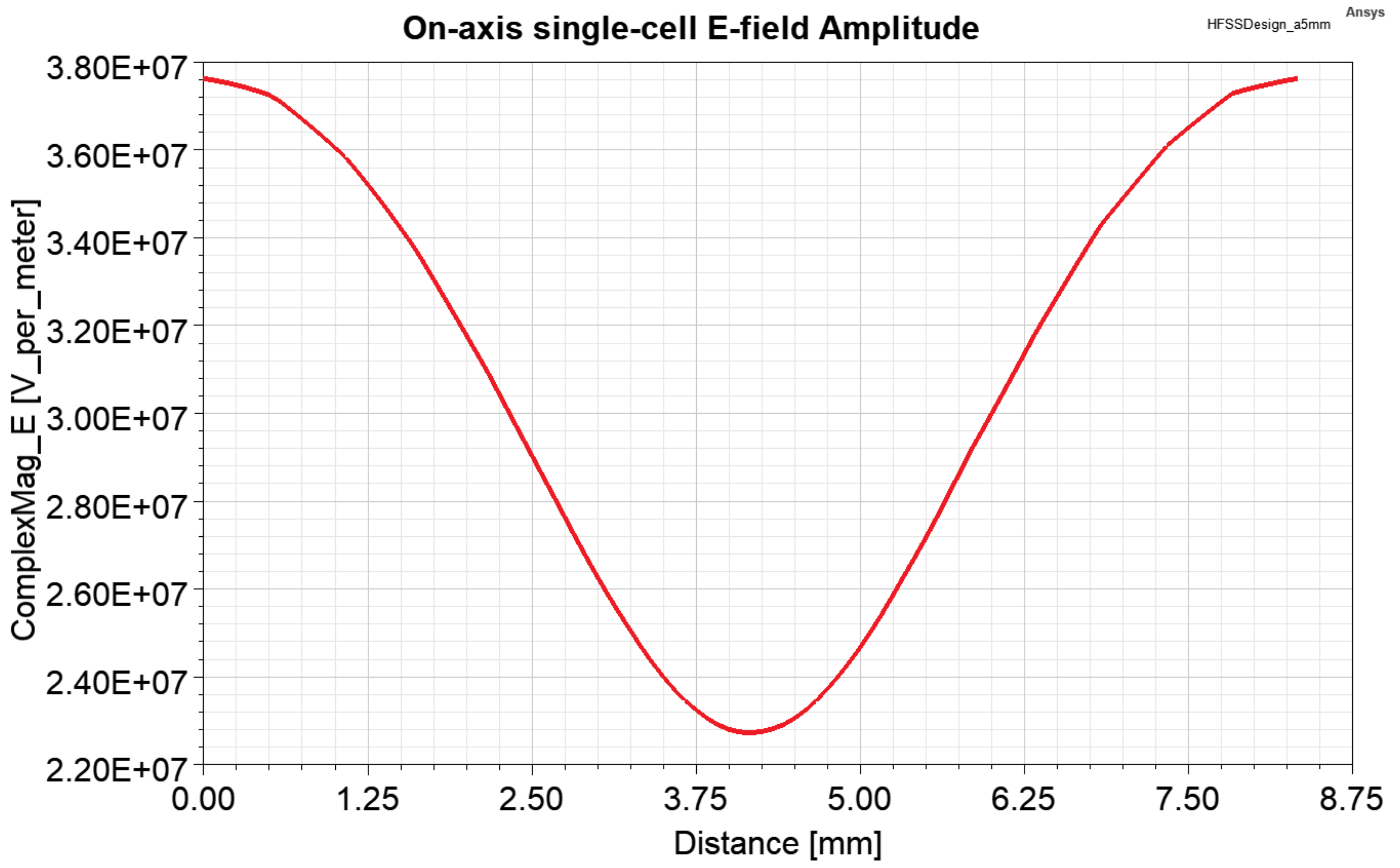
- e-beam σ_x= 1.5-2 mm
  - cavity iris radius a=4mm
- Cavity Length = 10 cm
- 2pi/3 mode
- Accelerating Gradient
  - TW option Eacc = 16.5 MV/m
  - SW option Eacc = 16.3 MV/m

RF design – first step

Comparison

- TW structure, constant impedance
- SW structure





Courtesy of L. Faillace

a = 4 mm	TW	SW
f	11.9942 GHz	11.9942 GHz
Q	6600	8,600
Vg	3.6 %	-
r	85.3 MΩ/m	80 MΩ/m
Eacc	16.5 MV/m	16.3 MV/m
alpha	0.63 1/m	-
Lt	10 cm	10 cm
Coupling β	-	2
Fill time Tf	9.3 ns	-
Build up τ	-	76 ns*
Pin	3.2 MW	0.37 MW

* If we want same filling and build-up times for both structures:
Tf = τ = 9.3 ns → β=22 → Pin SW = 2 MW

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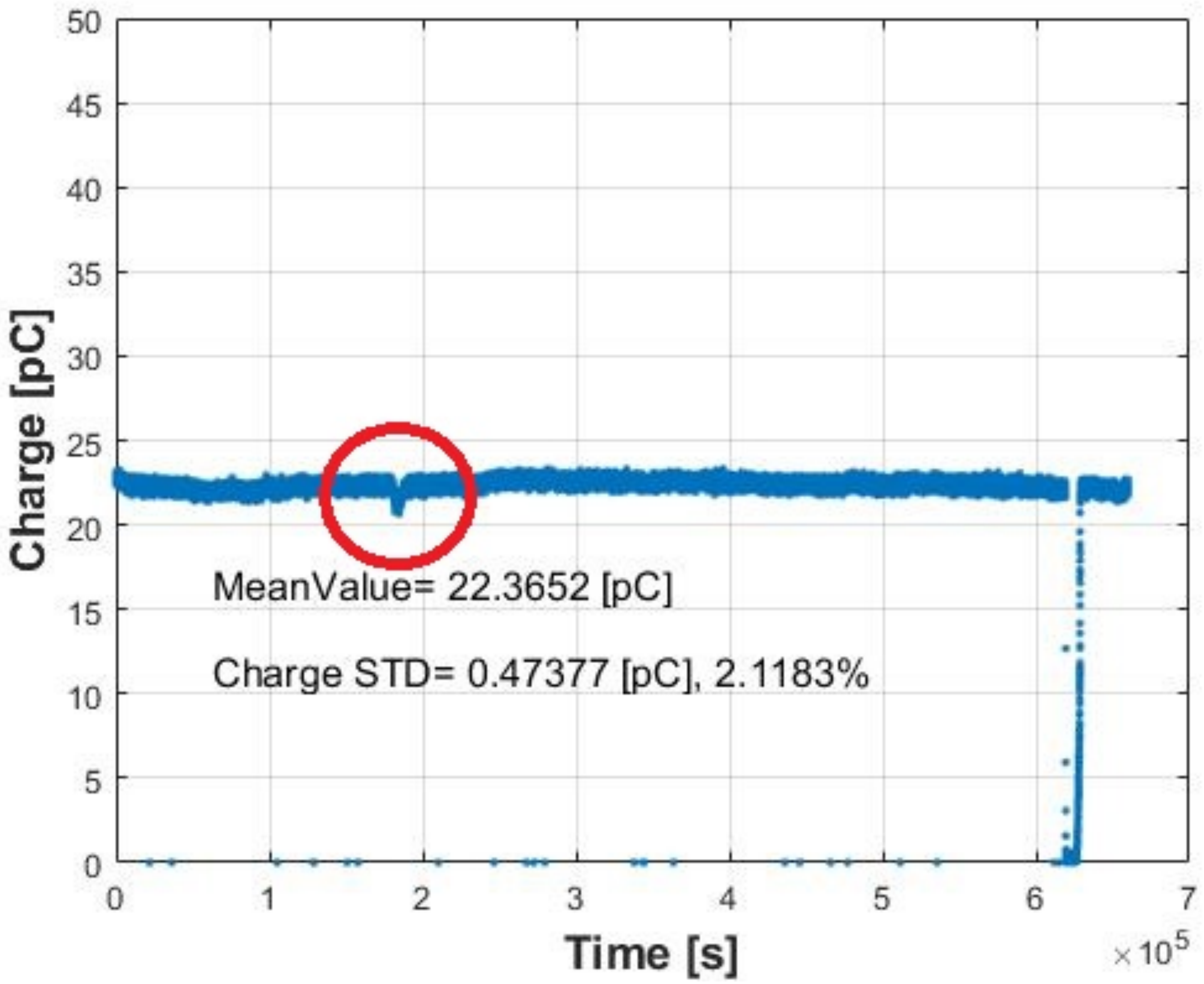
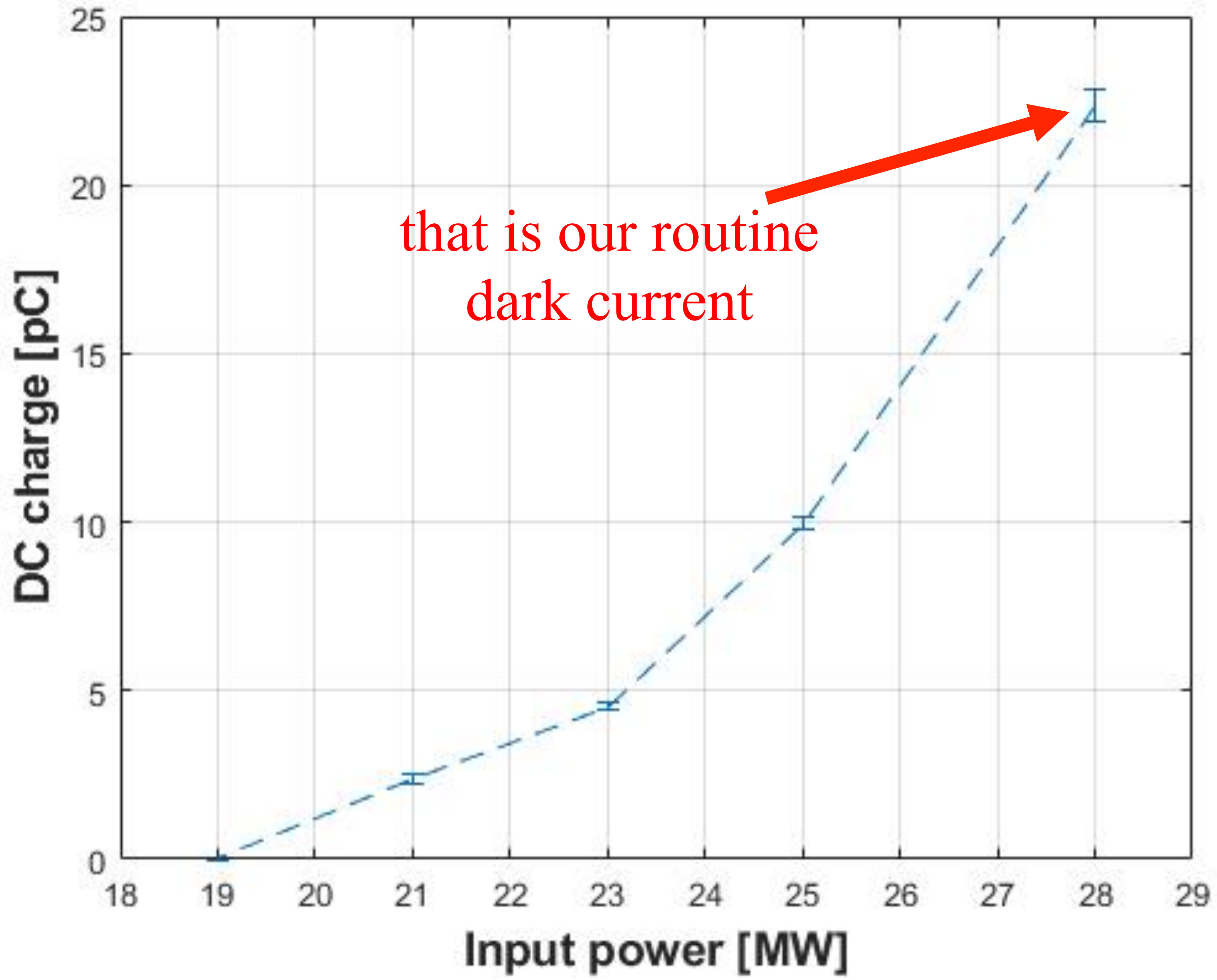
SPARC_LAB RF Gun Commissioning

Courtesy of V. Shpakov

- Operation at higher energy: 5.8 MeV vs 5.2 MeV (keeping fixed the injection RF phase at 40 deg from the zero-crossing)
- At the nominal power at the klystron exit (28 MW) the dark current produced by the gun is ~20 pC => At the same input power the old gun was producing 1.5-2.0 nC
- Breakdown rate is practically zero: a 24 hour long measurements of the dark current.
  - One suspicion event: most likely a short drop in power





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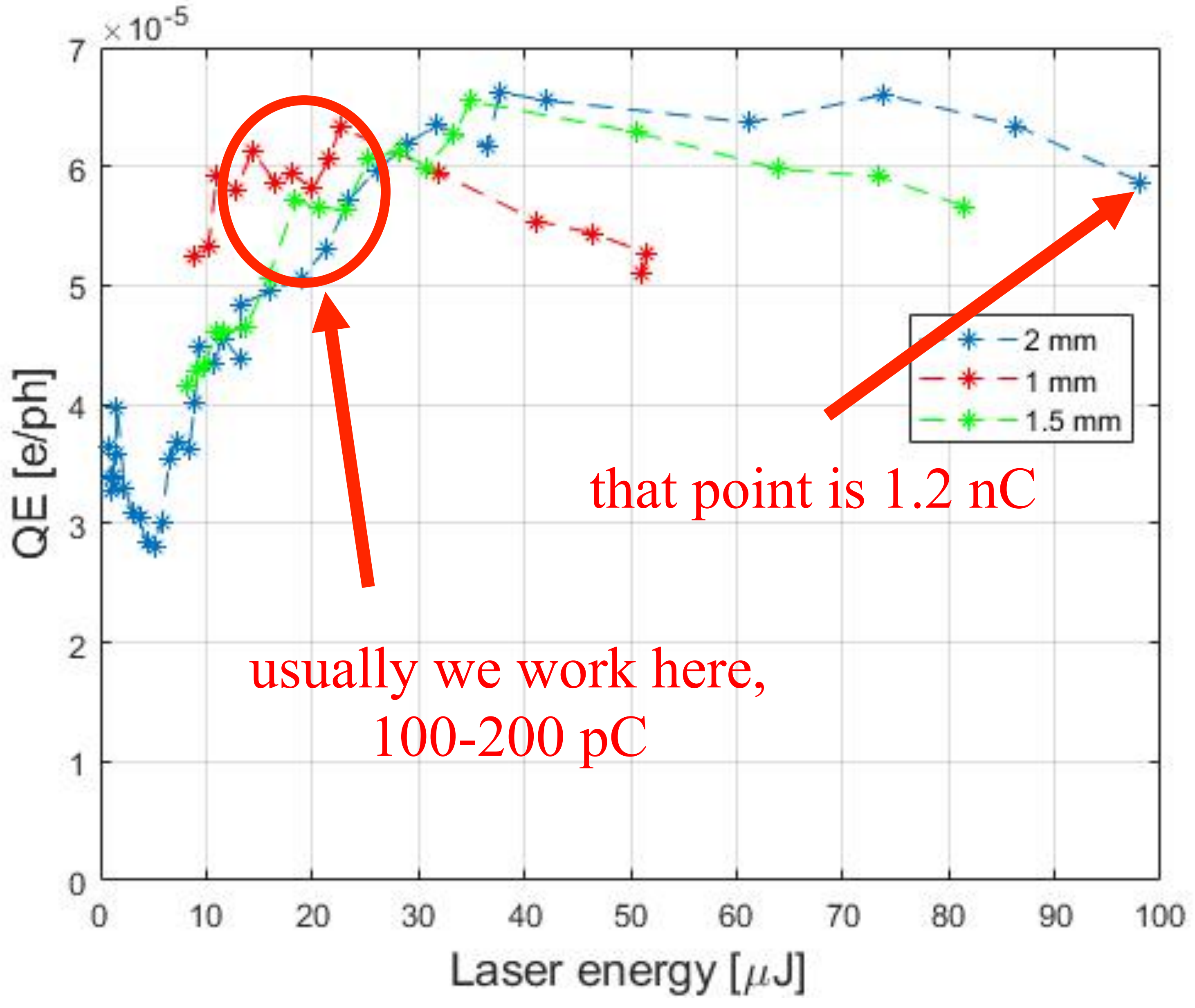
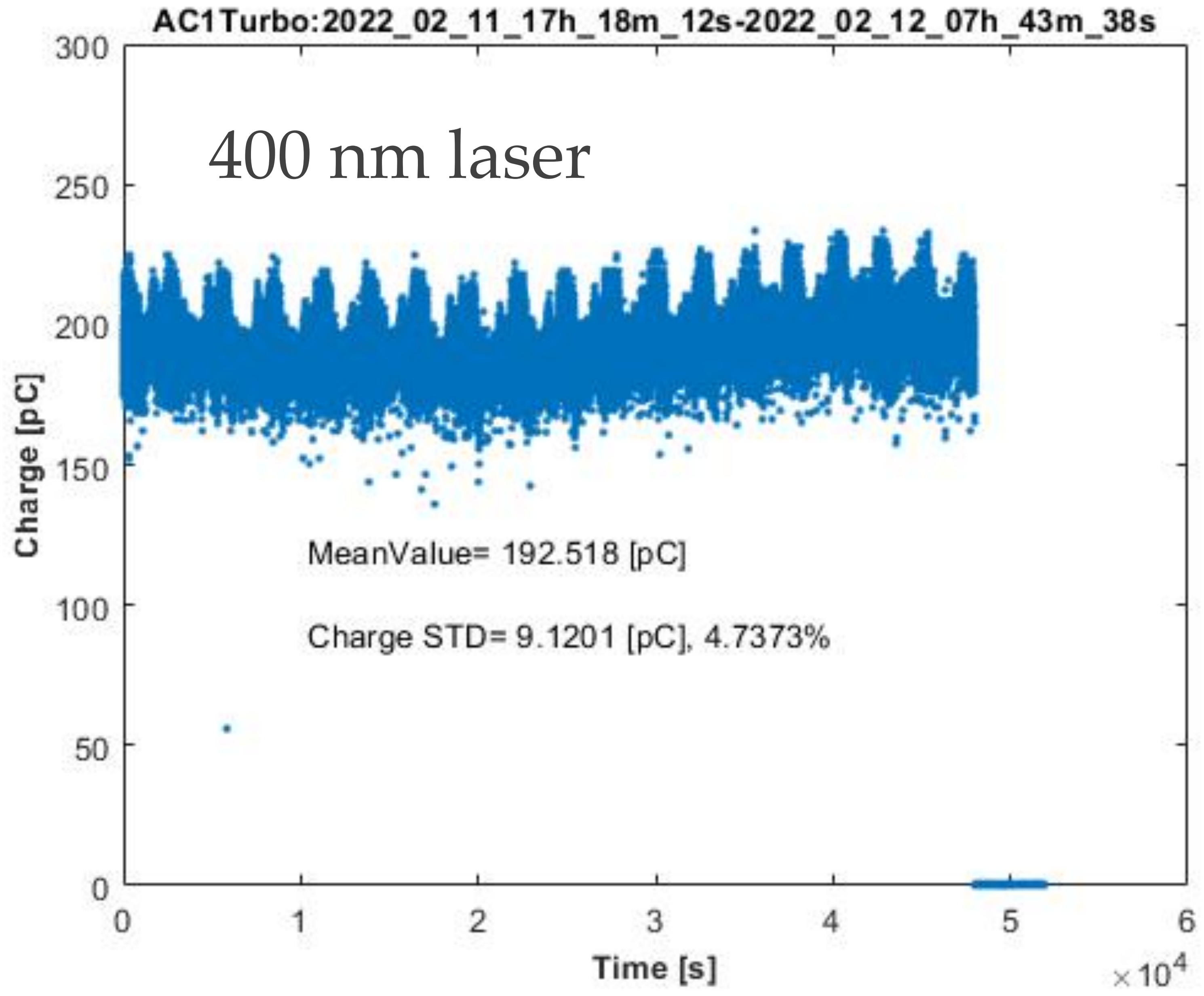
SPARC_LAB RF Gun Commissioning

Courtesy of V. Shpakov

- Quantum efficiency ~ 6.0×10^{-5}, which is a usual value for Cu cathodes
- Laser stability in a long period time, ~12 hours
  - Long, periodical instability due to thermal effects

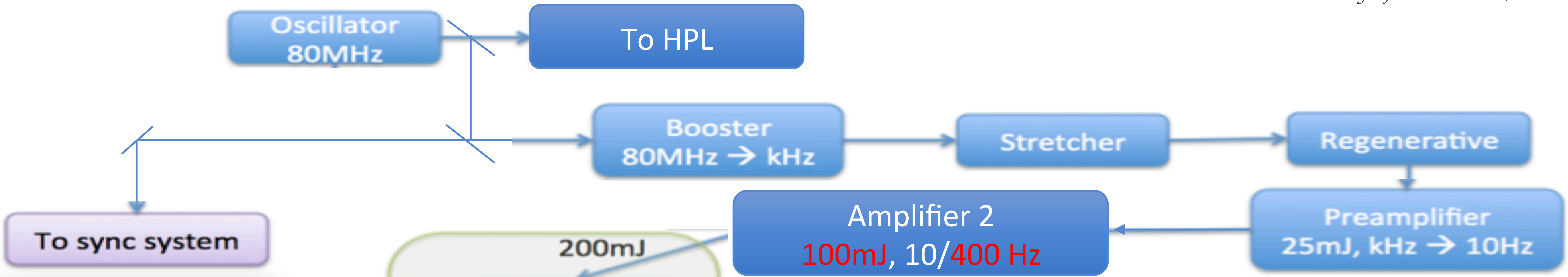




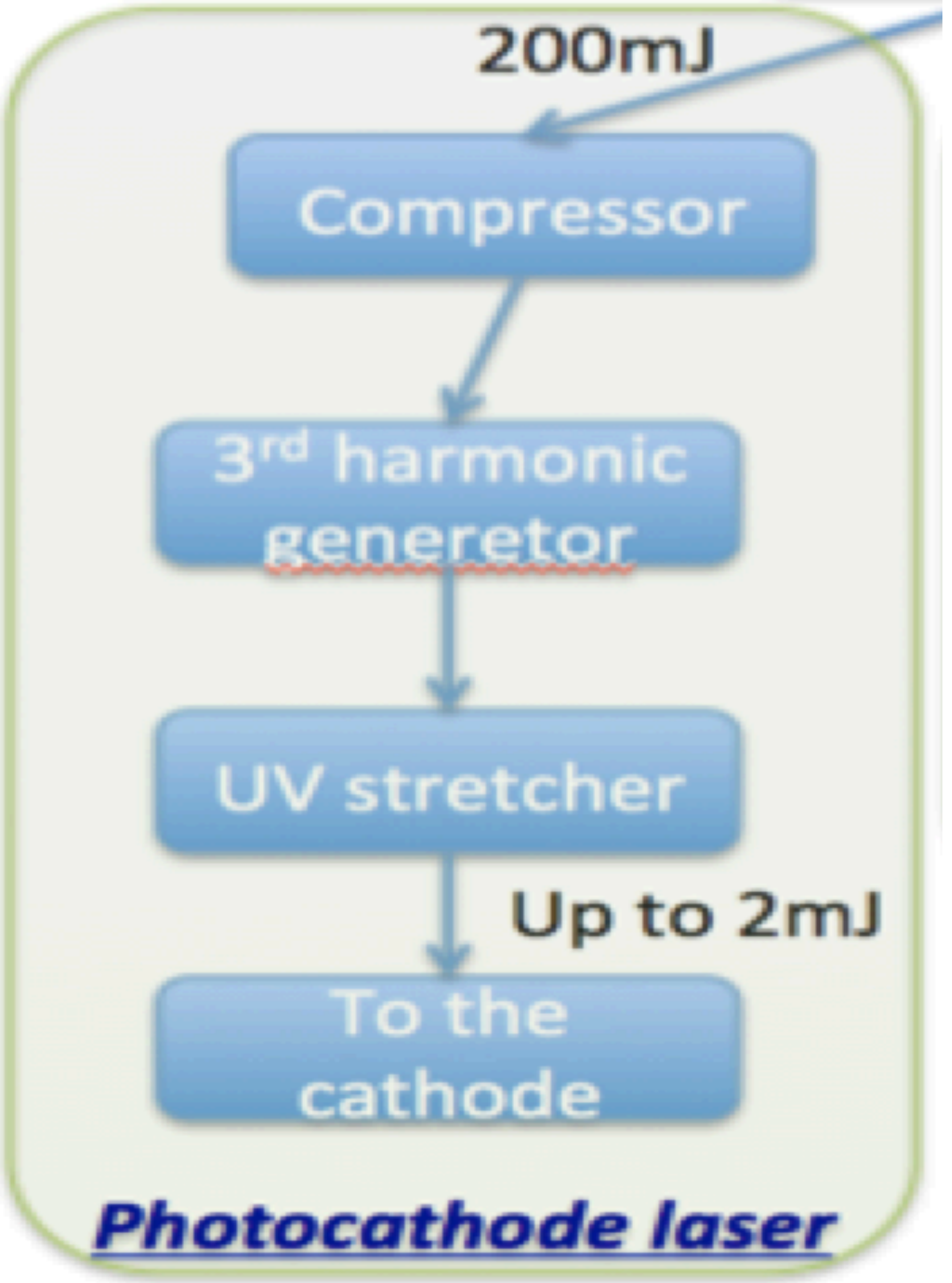
- New gun more comfortable from operational point of view, i.e. new laser injection system, motorized solenoid, …)
- Peak field at cathode ~112 MV/m
- Two order of magnitude drop in dark current:
  - 22 pC vs 1.5-2.0 nC
- Very low breakdown rate
- Transverse normalized emittance as expected from simulations

Laser Setup: 400 Hz upgrade

Courtesy of M. Anania, M. Galletti



ARCO H
Hybrid 1kHz/10Hz
4 mJ 1kHz + 25 mJ / 100 mJ / 500 mJ
4 W + 0,25 W/ 1 W / 5 W
< 100 fs / 35 fs

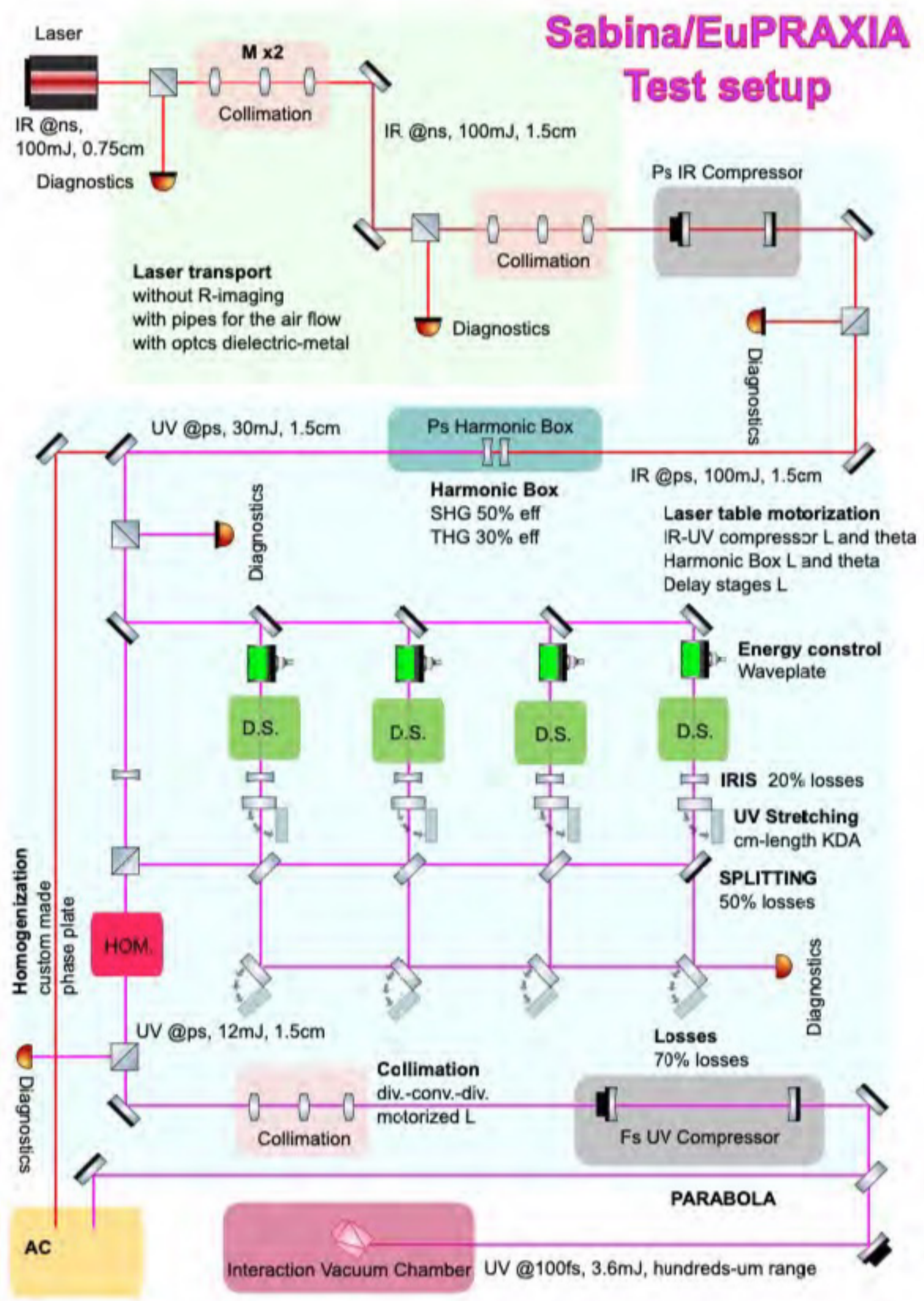


- In the framework of SABINA, the laser with kHz option has been bought to be installed and test at SPARC_LAB
  - 4mJ output at 1 kHz
- A laser test at 400 Hz option requires
  - the KHz compressor
  - a Pockell-cell to downgrade the rep-rate from 1 kHz to 400 Hz;
  - additionally, an optical amplifier (to go from 4mJ to 20/25mJ before compression)

Photocathode Laser

Study on the 400 GHz option

- The IR beam will be used in a «long» configuration (>1ns);
- After, it will be converted in UV (high efficiency);
- Then it will be splitted in «n» lines (COMB config);
- Then profiles will be homogenized;
- UV stretcher will be the last element;
- The different length for the different beam of the COMB, will be done inserting dispersive elements (KDA for example).
- This version allows to have the highest flexibility



Courtesy of M. Anania, M. Galletti

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Optical Table near the Linac

Courtesy of M. Anania, M. Galletti

UV Stretcher (>50 fs)

Parabola

Cathode

UV stretcher is essential to be able to go to very short pulses and have full control and more UV energy.

UV CCD camera (UV reflected from the cathode)

IR CCD camera (72°)

Autocorrelator

Energy

Virtual cathode

Pointing

HeNe laser for allignment

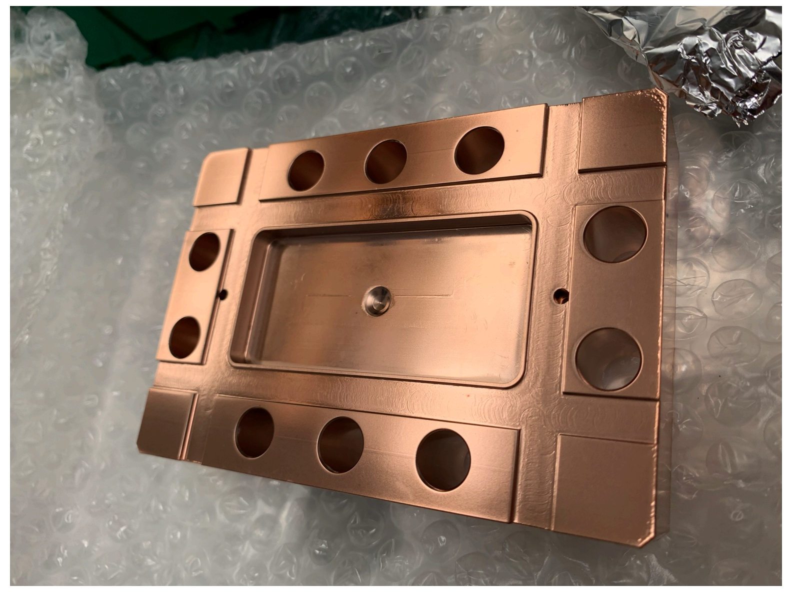
In this way, the optical table near the cathode has more or less the some dimension of the optical table that is now in SPARC (100x150).

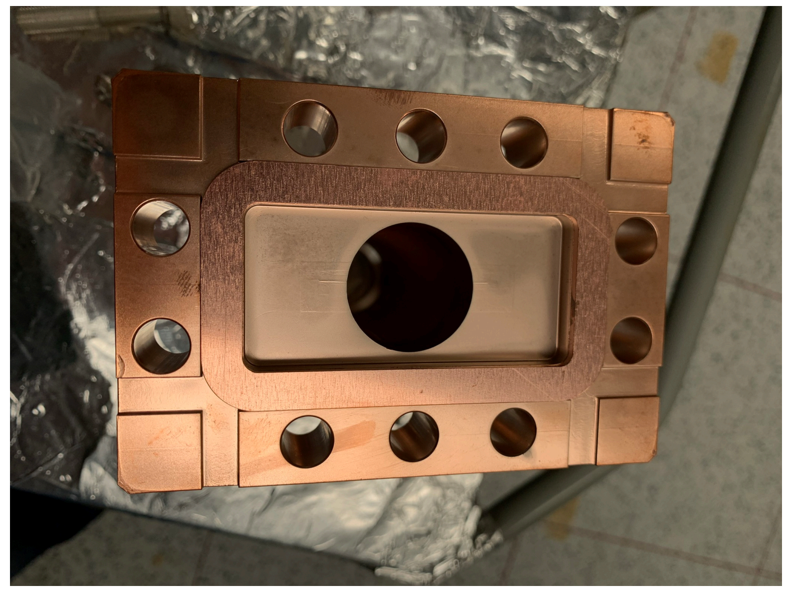
S-band RF Power Distribution

Courtesy of F. Cardelli

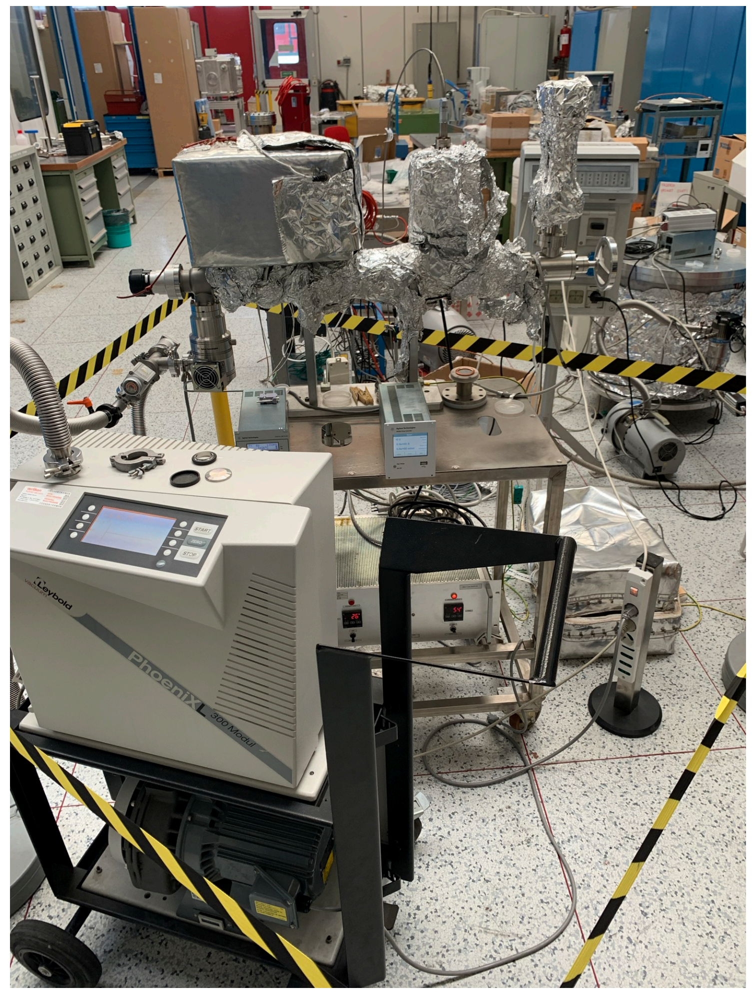
- The **"DESY-like" flange** adapted for S-band WR284 waveguides, has been **successfully tested**. Two flange prototype (see figures) have been realized (steel and copper plated steel). They were tested by performing vacuum leak test before and after several thermal cycles of heating and cooling, up to a maximum temperature of 255°C. The **main advantages** with respect to the "LIL" and "SLAC" type are: **ease of assembly**, **greater vacuum seal** and **mechanical strength** once tightened.
- Some new components (T-pumping unit, bend…) will be realized with this flange and installed at SPARC after RF low power test and vacuum test.
- A C-band Isolator SF6 free (CML) has been ordered in the framework of the IFAST project. It should be shipped by the end of April, and it will be tested with RF power at PSI. This is an important test also for the Eupraxia@SPARC_LAB injector in view of an S-band isolator SF6 free (and also for an X-band version).

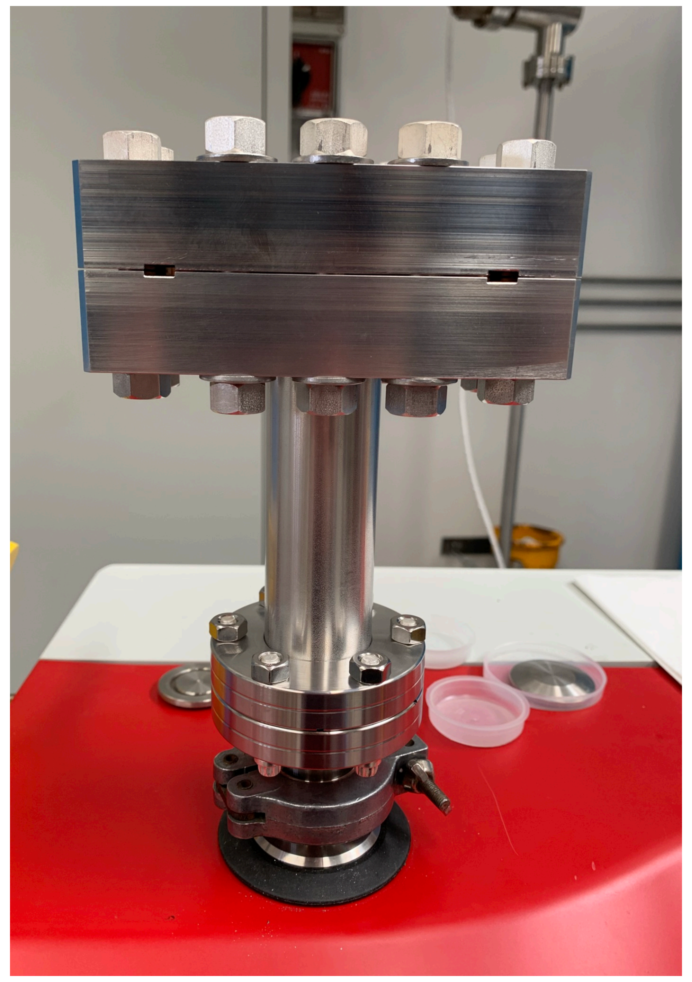
New S-band "DESY-like" flange





Setup for the thermal and vacuum leak tests





(Courtesy of V. Lollo)

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S-band RF Power Station

Courtesy of F. Cardelli

- Different improvements (Modulator, Control system, etc) have been performed for the X-band source currently installed at TEX, in particular on the monitoring of the modulator parameters, and also the S-band sources will benefit for this upgrades.
- A survey of the commercial S-band klystron @100Hz has been performed.
  - Two options of S-band klystron for the injector are the most suitable:

Vendor	Model	Freq. [MHz]	Peak Power [MW]	Pulse length [us]	PRF [Hz]	Vk [kV]	Ik [A]	Eff. [%]	Gain [dB]
THALES	TH2128C	2856	**45**	**4,5**	**100**	320	360	43	54
CANON	E37314	2856	**60**	**4**	**100**	360	412	41	53

- CPI produce low power (up to 5MW) S-band pulsed klystrons

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Klystron Phase Stabilization

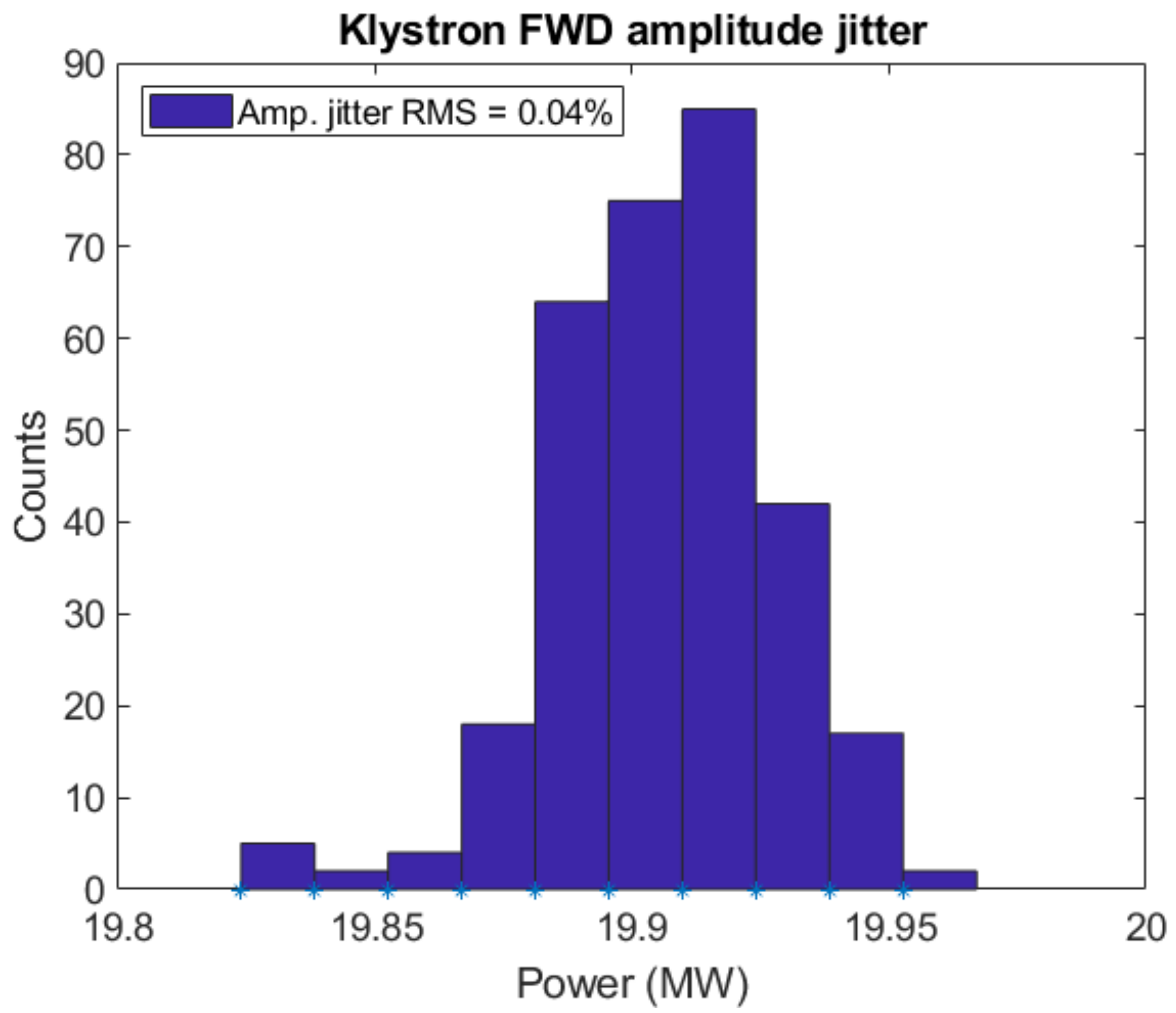
Courtesy of M. Bellaveglia

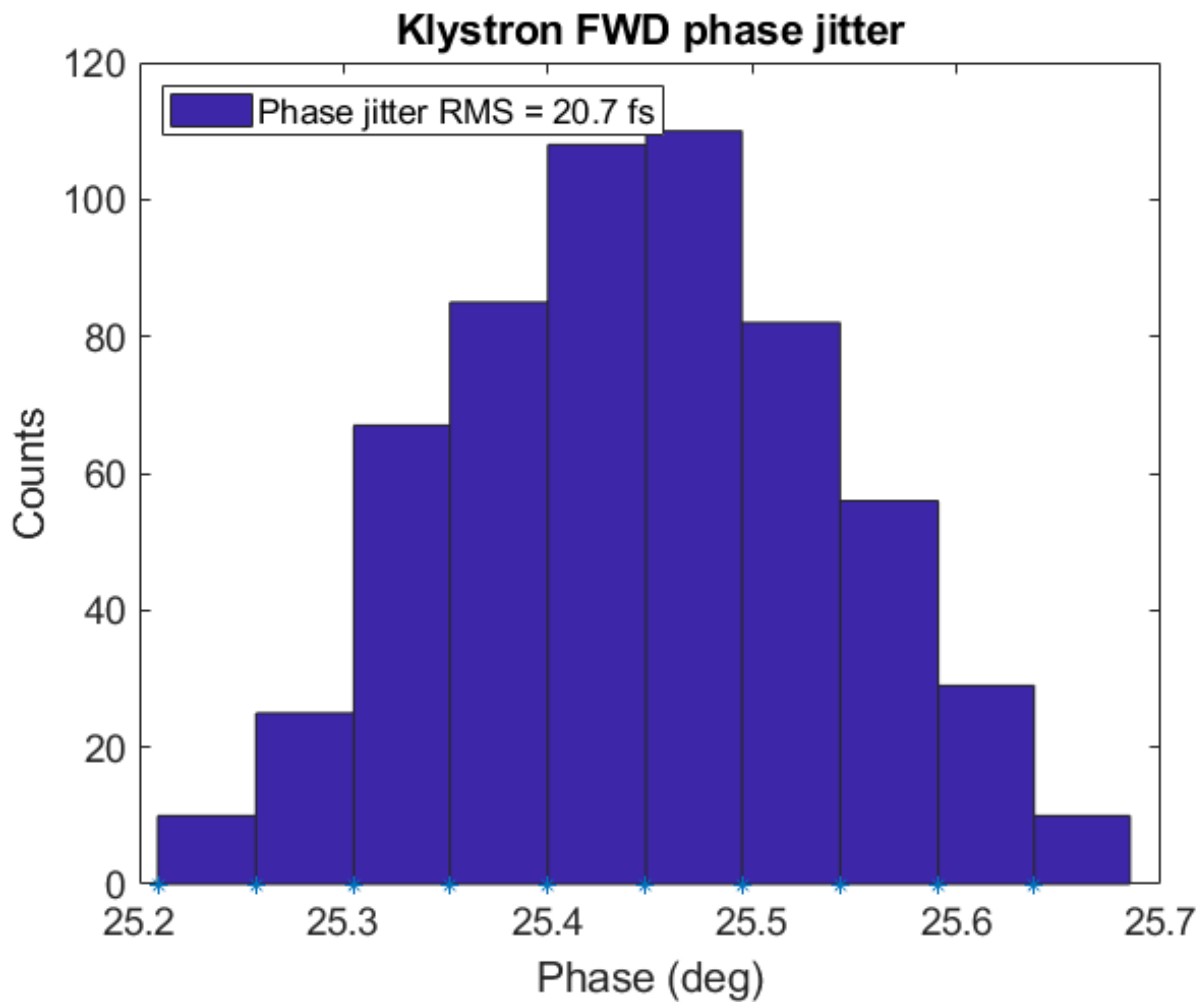
- **Feed-forward circuit implementation => to stabilize the phase**
  - The aim of feed-forward is to correct the klystron output phase jitter due to the modulator HV fluctuations (typical in PFN modulators) within the same RF pulse
  - We have produced an electronic prototype and it is ready to be tested in the SPARC S-band power station
  - We have scheduled the test in the next SPARC run (within the end of 2022)
- **Feedback implementation (klystron loop):**
  - This system is already in operation in the SPARC PFN modulators of the S-band power stations with good performances (jitter reduced from hundreds to tens of fs)
  - We need to test the performance of such a system in a power station equipped with a solid state modulator to try to further minimize the phase jitter in the klystron RF output pulse (presently of the order of 20÷30 fs RMS)
  - We are purchasing the electronic components (namely the fast phase shifters) to test the analog feedback system in the SPARC C-band power station (equipped with a solid state modulator)

Stability Measurements at TEX

Courtesy of M. Bellaveglia

- We measured the TEX X-band power station (with solid state modulator) stability
- Both amplitude and timing jitter have been measured
- The measurement is performed using the dedicated digital LLRF with a resolution of ~15 fs
- As expected the performance is much better than a power station employing PFN modulators (typically amplitude jitter 0.2÷0.3% and timing jitter < 500 fs RMS w/o fbk and < 50 fs RMS with fbk)





Timing System

Courtesy of A. Stella

- It aims at the 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
  - **Micro Research Finland** has been selected to provide hardware for a prototype system, consisting of MicroTCA boards:
    - Master Generator board
    - 2 Receiver Boards with 8 delay channels
  - Tendering and purchase order procedures have been completed
    - **delivery** time 16 weeks (**oct 2022**)
  - Tests will start afterwards together with development of dedicated Epics software
    - **Installation and test @ SPARC_LAB expected to begin in Jan 2023**

Magnets & Power Supply

Courtesy of L. Sabbatini, A. Vannozzi

Work on magnetic design is ongoing: see table below

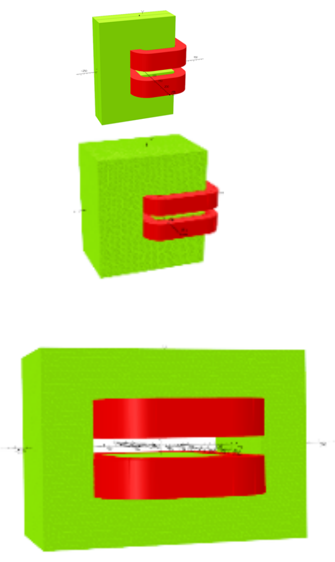
- ☹ Unfortunately our PhD student has left in January due to a job offer

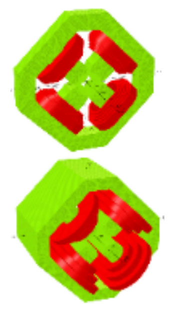
- ☺ Upgrade of magnetic measurements laboratory:

  rotating coil from CERN for measures of multipoles (suitable for EuPRAXIA quad sizes) – LATINO project

  starting the design of a mole Hall probe (suitable for EuPRAXIA undulators) – hopefully PNRR IRIS project

DIPOLES	Description	Field (T)	L_{mag} (mm)	θ	Status
BLH	4x laser heater chicane	0,6	120	70 mrad	Preliminary design done, optimized
BC2	4x compressor chicane	0,7	300	87 mrad	Preliminary design done, optimized
BC4	5x driver removal		(250)		Mag. design ongoing
DISPSPL	Spectrometer	0,94	260	14°	Design done, optimization ongoing
DISPSPH	Spectrometer		(400)		Mag. design ongoing
ONEGEV	Dump		(600)		Still to be designed
QUADS	**Description**	**Integrated Gradient (T)**	**L_{mag} (mm)**	**Gradient (T/m)**	**Status**
Fam. #1	First guess L_{mag} = 100 mm	1,5	100 → 68	15 →22	Preliminary design done, optimized
Fam. #2	First guess L_{mag} = 150 mm	3	150 → ….	20 →….	Design done, optimization ongoing
Fam. #3	First guess L_{mag} = 200 mm	7	200 → ….	35 → …	Mag. design ongoing





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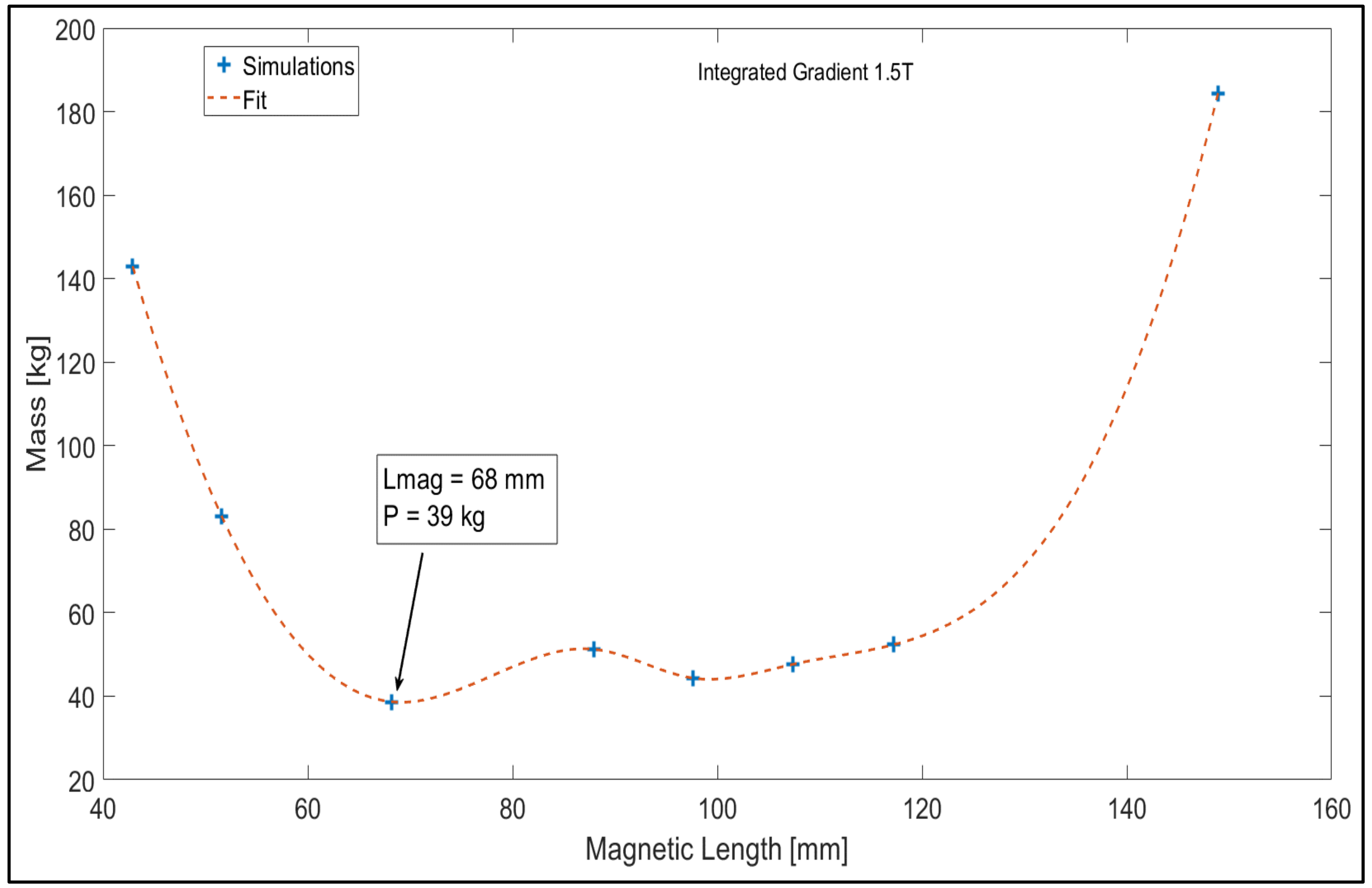
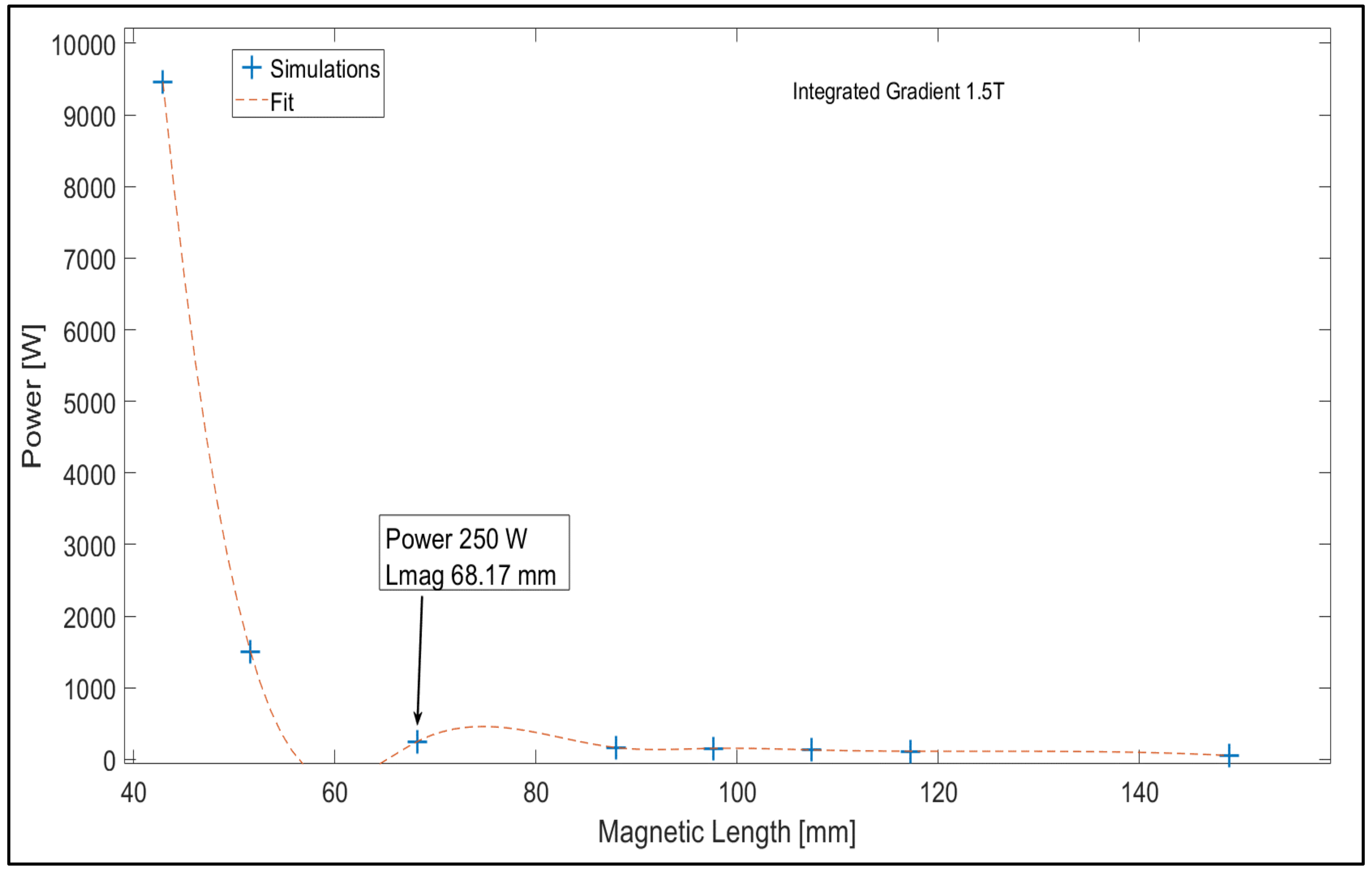
Magnets & Power Supply

Courtesy of L. Sabbatini, A. Vannozzi

Quadrupoles Optimization

- A complete tool for the design has been developed
- Several simulations have been performed to find the power consumption and mass (installation costs) optimum
- An optimum was found for 1,5T integrated gradient quadrupole, optimization is ongoing for the other two families





Conclusions

On going	To Do
✓ Comb beam => S-band injector optimization ➢ **Essential 35 MV/m** in the 2m long S-band TW ✓ Optimization of x-band linearizer for the 2+2+2+2 layout => 4 mm iris ok ➢ Cost-benefit analysis: TW requires too high power kly; SW requires circulator!!	➢ Evaluation with integrated x-band linearizer ➢ SW vs TW x-band linearizer ➢ Jitter sensitivity studies ➢ Laser heater project - Subject to the definition of the injector
✓ Successful commissioning of the new RF gun at SPARC_LAB with electrons	
✓ Acquisition of the photocathode laser with kHz option (=> 4mJ output at 1KHz) ✓ Preliminary layout of the injection line	➢ test of the 400Hz option: kHz compressor; Pockell Cell to downgrade the rep-rate from 1KHz to 400Hz; optical amplifier (to go from 4mJ to 20/25mJ before compression)
✓ **DESY-like flanges prototype for WR284 S-band waveguide** successfully tested ✓ **C-band Isolator SF6 free** (CML) ordered in view of an S-band isolator SF6 free (and also for an X-band version) ✓ Survey of the commercial S-band klystron @100Hz performed	➢ Definition of the number of S-band stations and choose of the klystron (It depends mainly on the choice for the working frequency: EU 2998MHz or US 2856MHz)
✓ BPM prototype designed (WP13 & Vacuum Group) and built (CINEL srl): Sized to be inserted in a 10cm long Quad with 25mm aperture ✓ Cavity BPM resolution measurement at SPARC_LAB	➢ Realization of a complete BPM suitable for beam tests
✓ **LLRF**: Full upgrade to digital LLRF (2 S-band and one C-band module) ready to be installed ✓ **Synchronization:** New fast phase shifter (response time 6.3 ns)	➢ Test KlyLoop su C-band SSD modulator at SPARC to check performances on short pulses to further reduce the SSD jitter (currently few 10s of fs)

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