SPARC_LAB latest results

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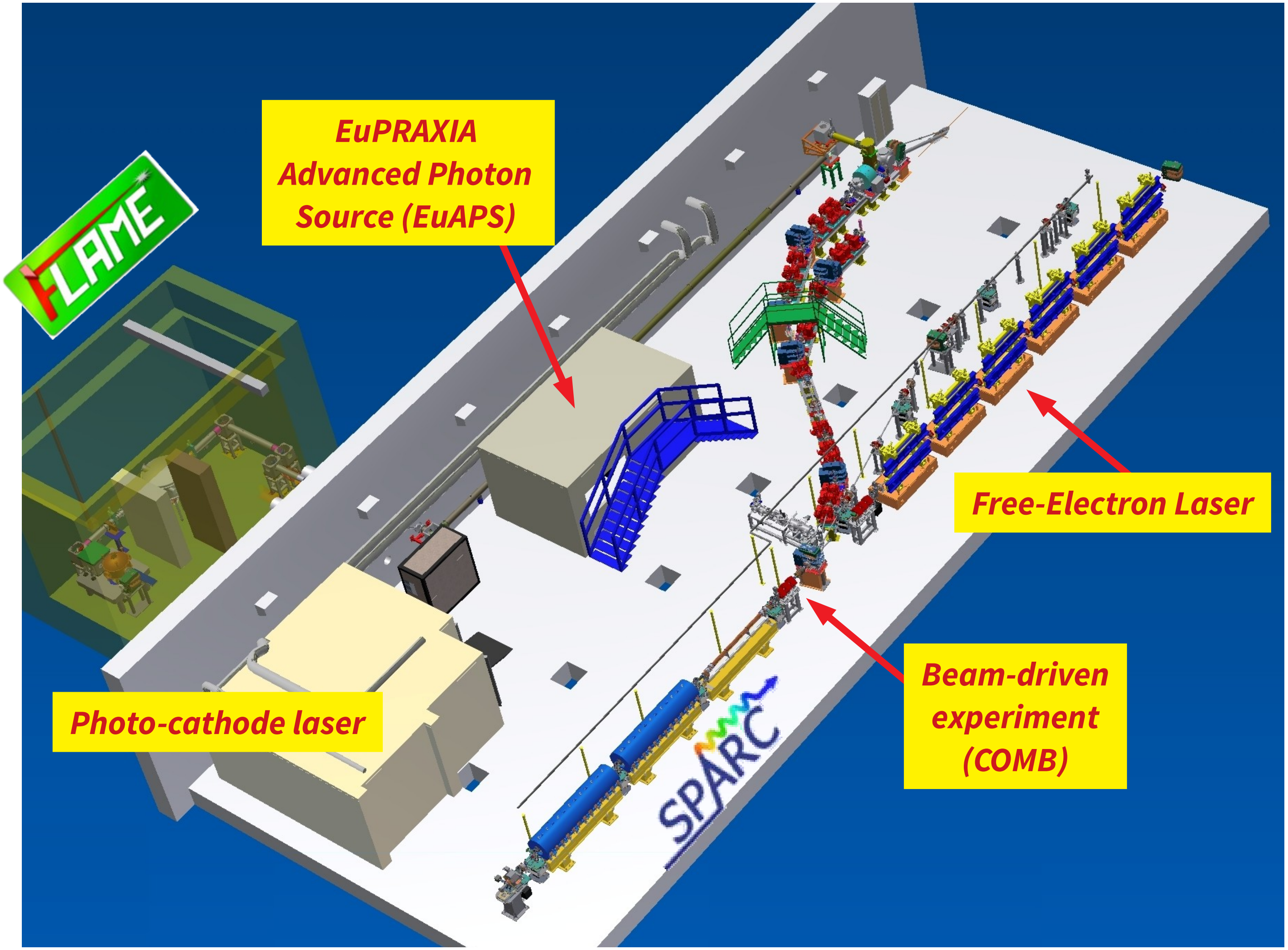
On behalf of the SPARC_LAB collaboration

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

SPARC_LAB facility



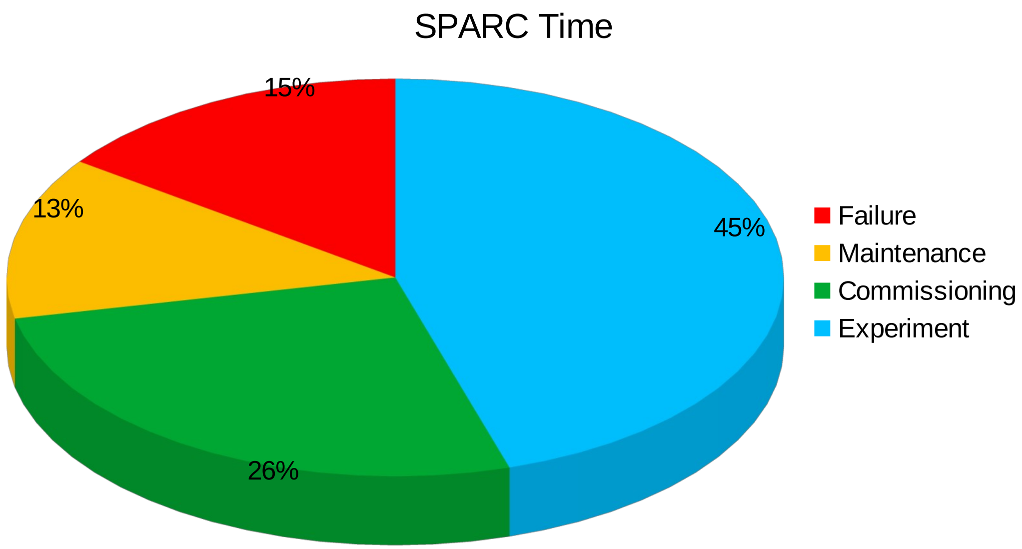
Ferrario, M., et al. "SPARC_LAB present and future." NIMB 309 (2013): 183-188.

SPARC uptime

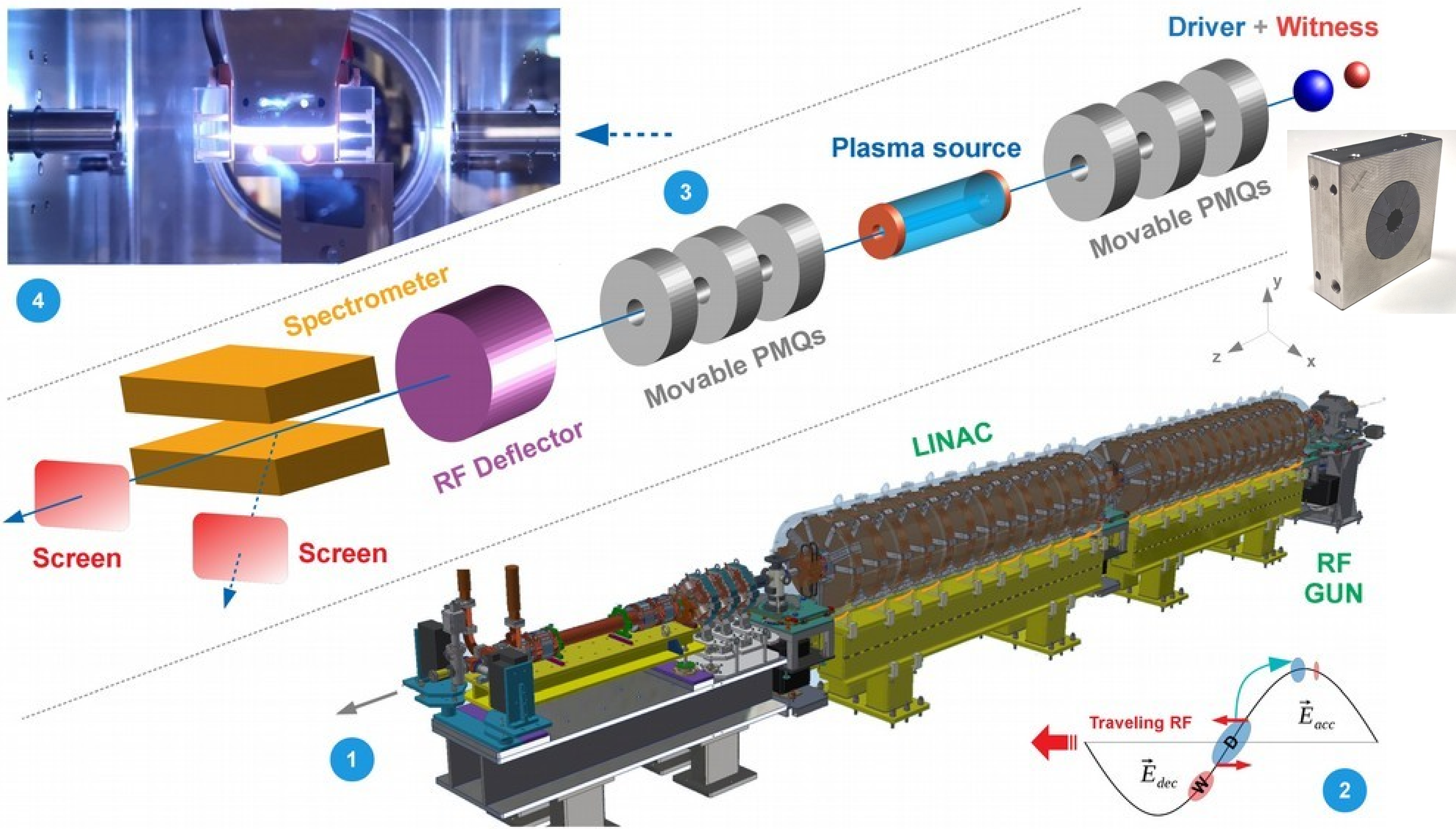
Scientific program

- *Demonstration of large accelerating gradient (>GV/m) [concluded]*
- *Plasma recovery time with Hydrogen at nanosecond delays [ongoing]*
- *Plasma ignition with laser filaments [postponed to 2023]*

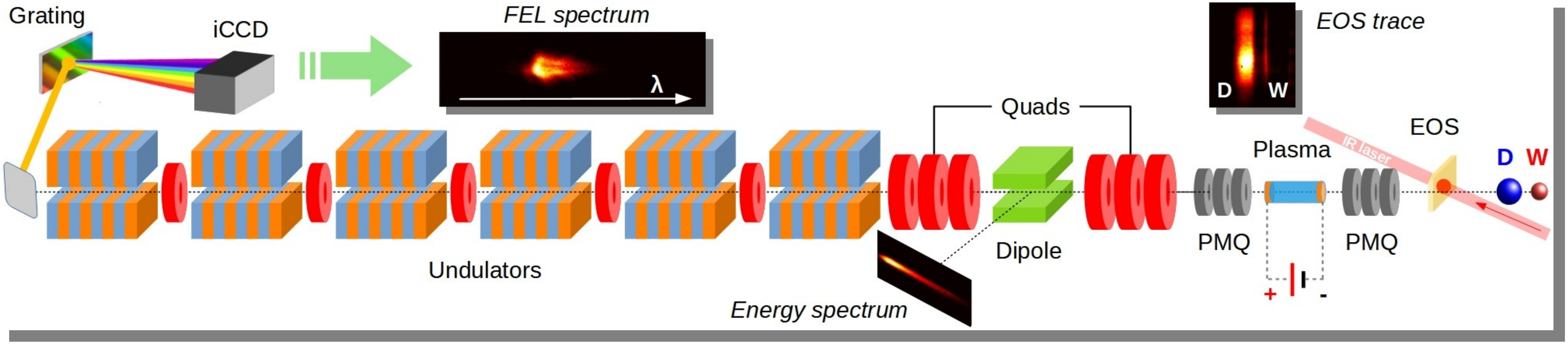
Only two months (October and November) dedicated to experimental activities. Stop from 5th December due to SABINA installations



Plasma acceleration experiment



Proof of SASE FEL driven by PWFA



Proof-of-principle experiment to demonstrate high-quality PWFA acceleration able to drive a Free-Electron Laser

Witness is completely characterized (energy, spread, X/Y emittance) allowing to match it into the undulators beamline

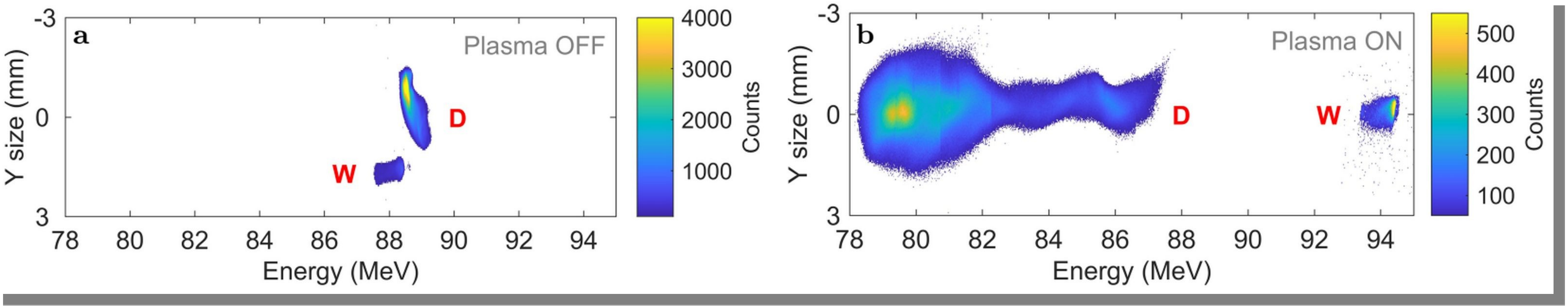
Jitter is online monitored with Electro-Optical Sampling (EOS) diagnostics

Imaging spectrometer with iCCD used to detect FEL radiation

In collaboration with

ENEA
Università di Roma Tor Vergata
SAPIENZA Università di Roma
Università degli Studi di Milano

Beam configuration at the FEL entrance



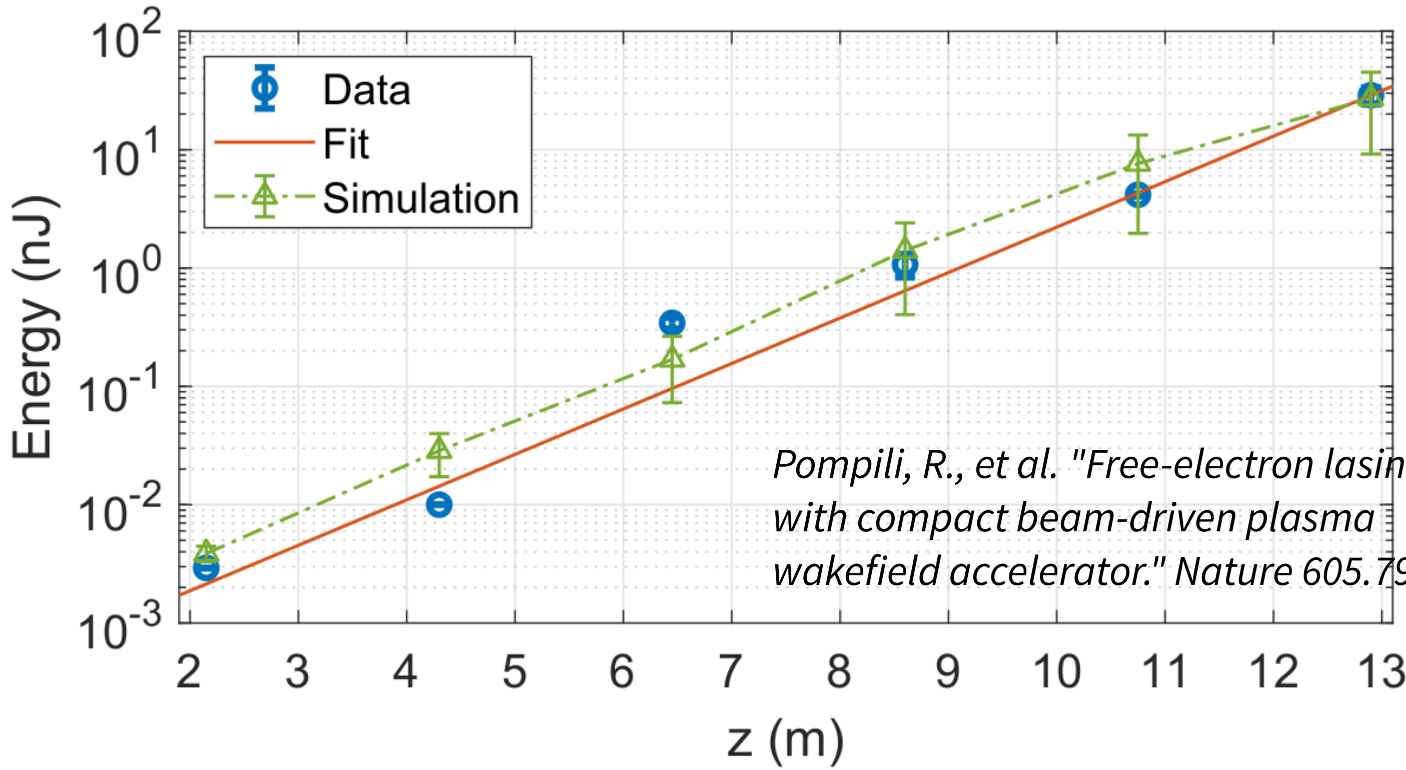
Plasma density set to 1.6×10^{15} cm^{-3}

Accelerated witness

- *Energy: 94 MeV, 0.3 MeV spread (~200 MV/m acceleration)*
- *Emittance: 2.7(X) um, 1.3(Y) um*

Driver decelerated by almost 10 MeV

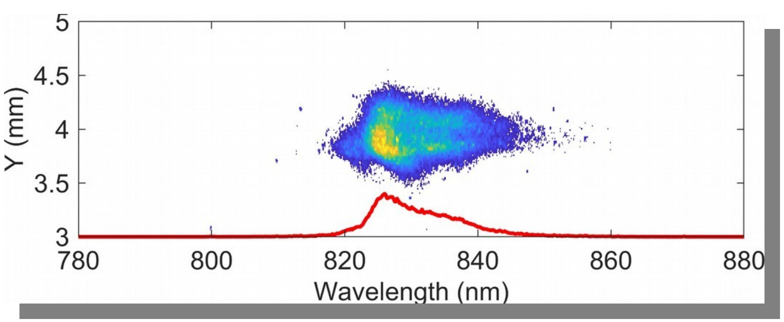
FEL driven by PWFA: exponential gain



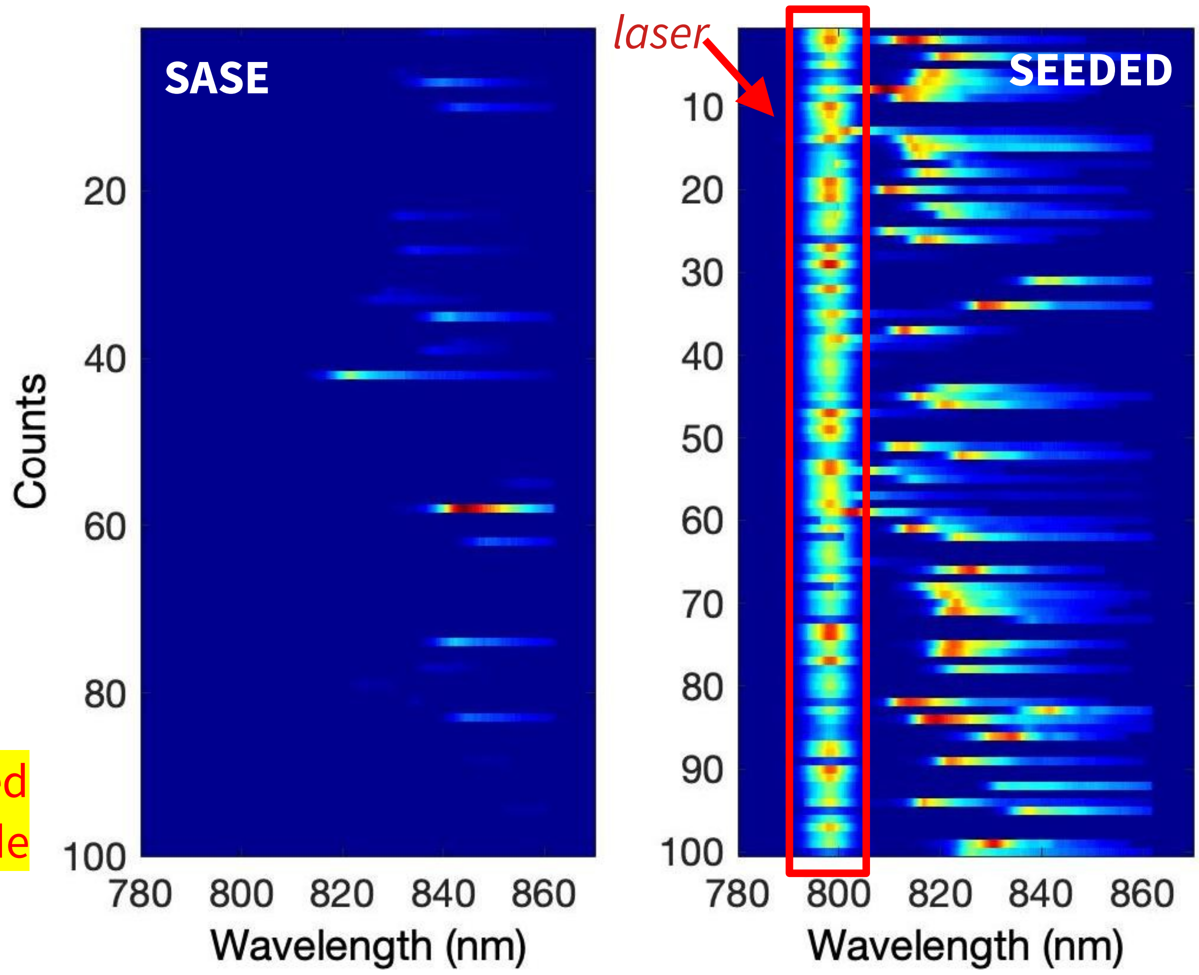
Pompili, R., et al. "Free-electron lasing with compact beam-driven plasma wakefield accelerator." Nature 605.7911 (2022): 659-662.

Exponential gain of FEL radiation (@ 830 nm)

Data taken with 6 (Si) photo-diodes downstream the undulators



Seeded FEL Performances



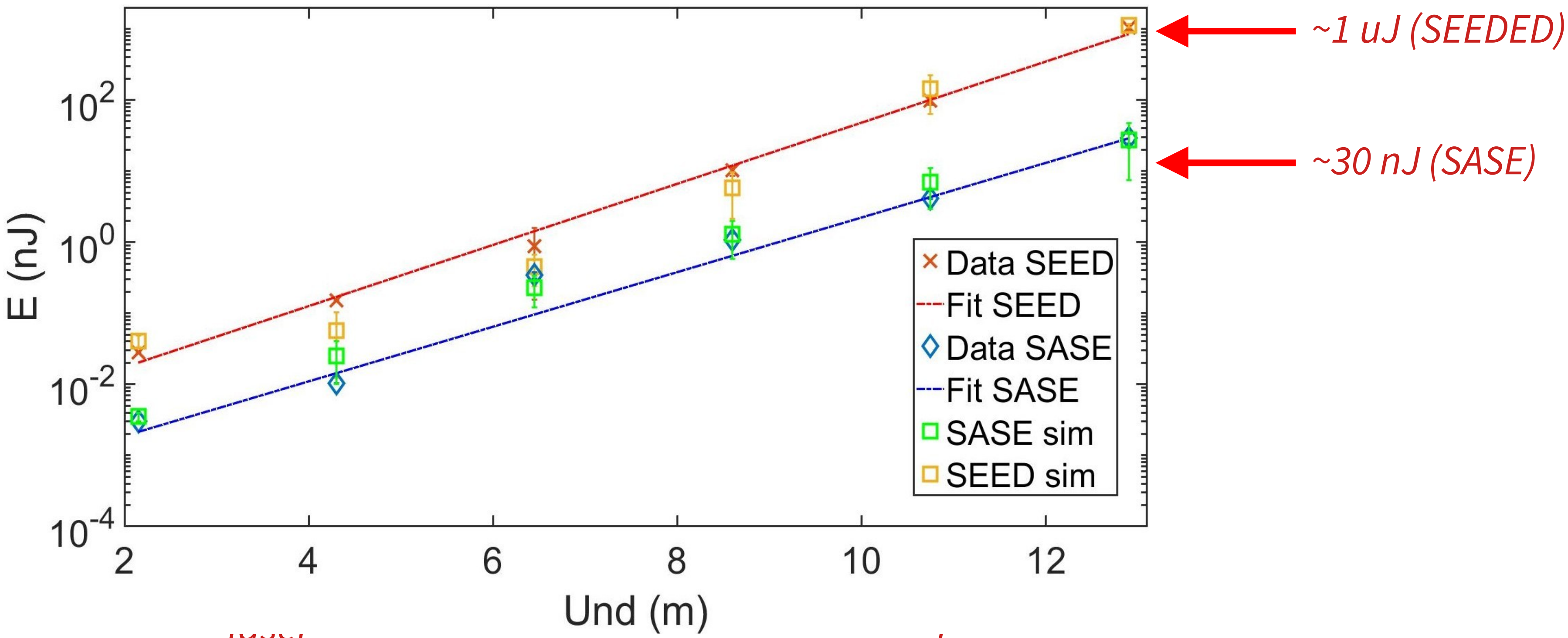
10^3 ND filter used @ 6^{th} photodiode

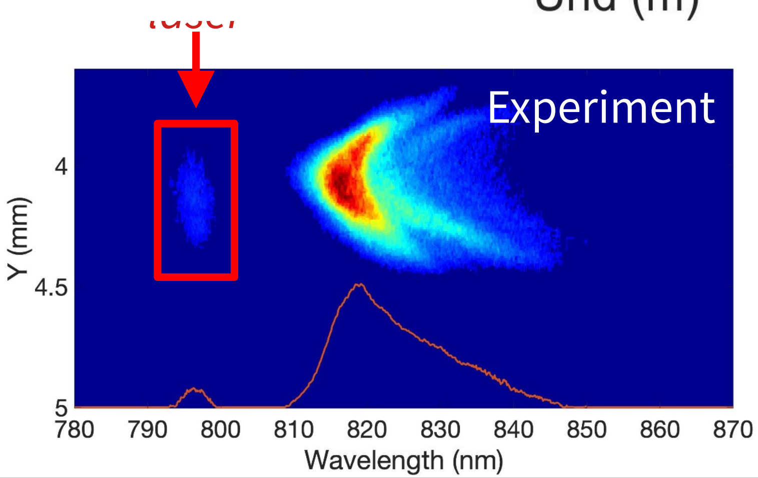
M. Galletti, et al. *accepted by PRL*

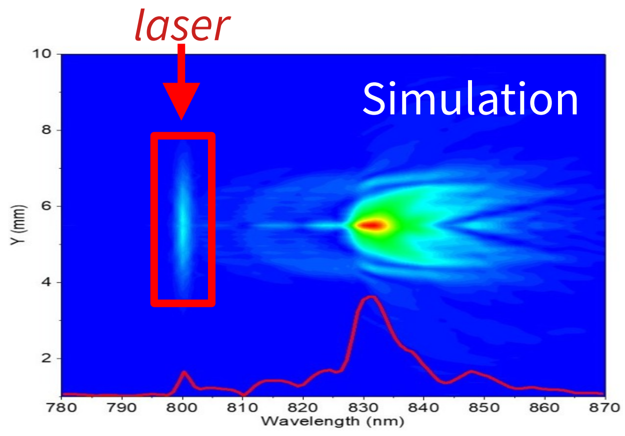
FEL radiation output is largely stabilized by the seed laser, larger output energy

Undulators tuned for FEL radiation at ~830 nm → separated from the laser (793 nm)

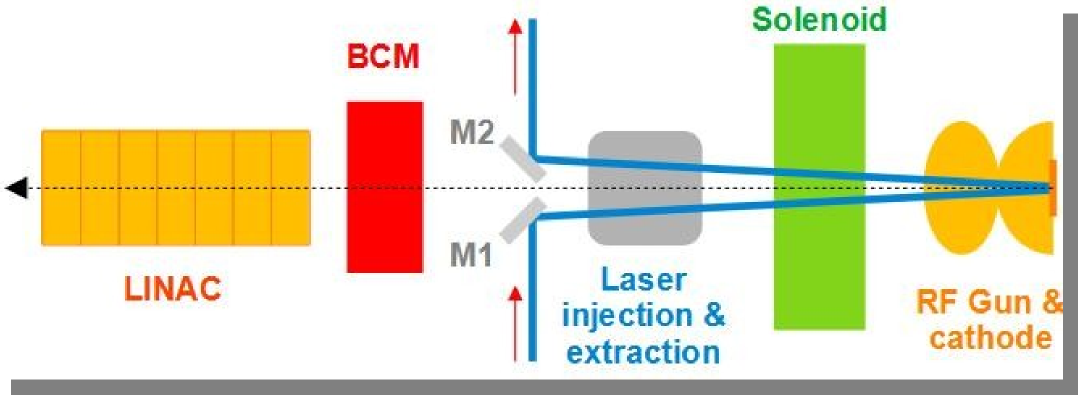
Exponential growth







UV/blue tests with the new RF gun

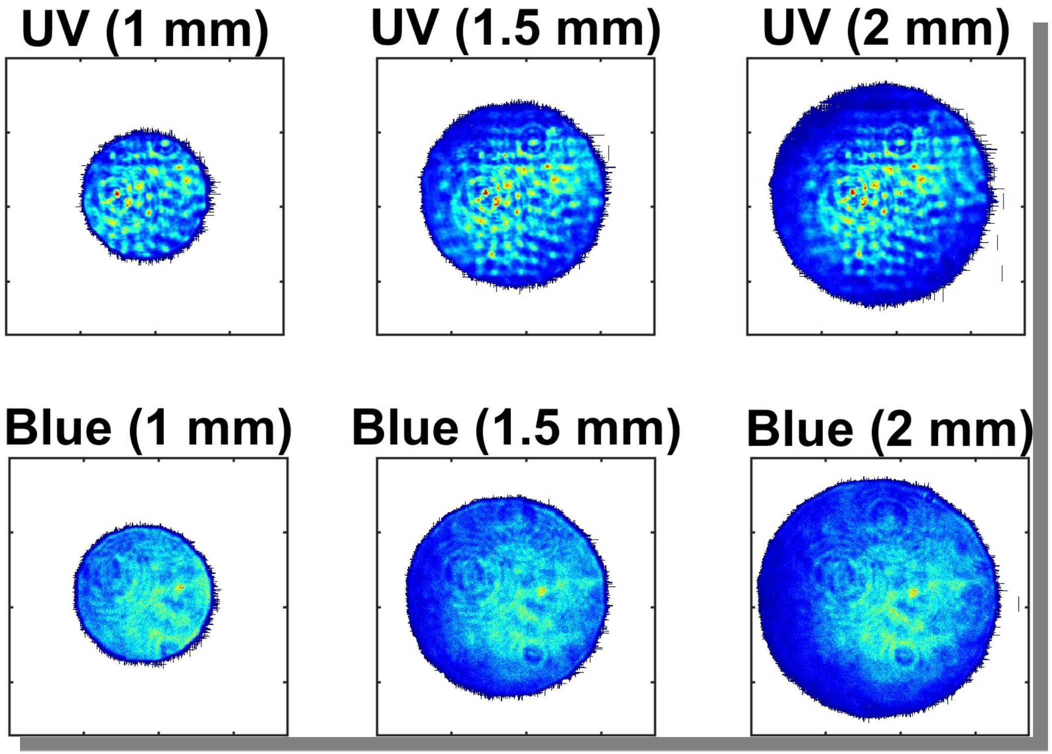


In February 2022 we spent few weeks investigating the photo-emission obtained using UV and blue laser pulses on cathode

- *Photo-emission from blue possible only with ultra-short laser (2-photons absorption)*

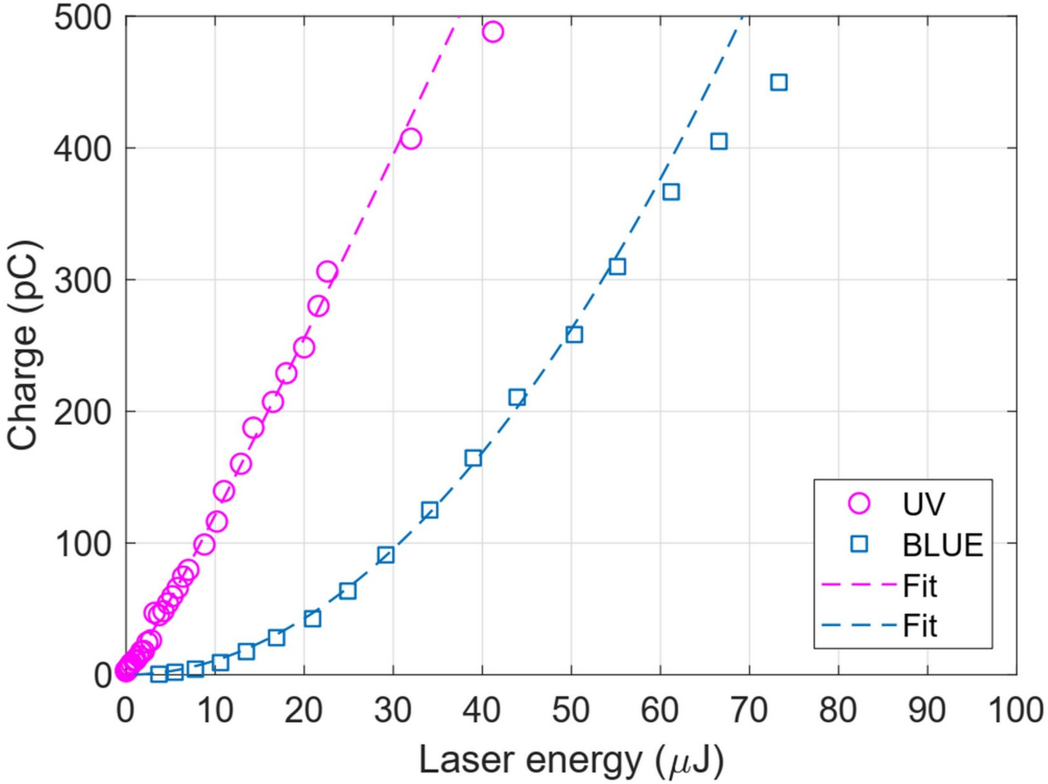
Goal: compare these results with old gun that showed larger QE when irradiated with blue

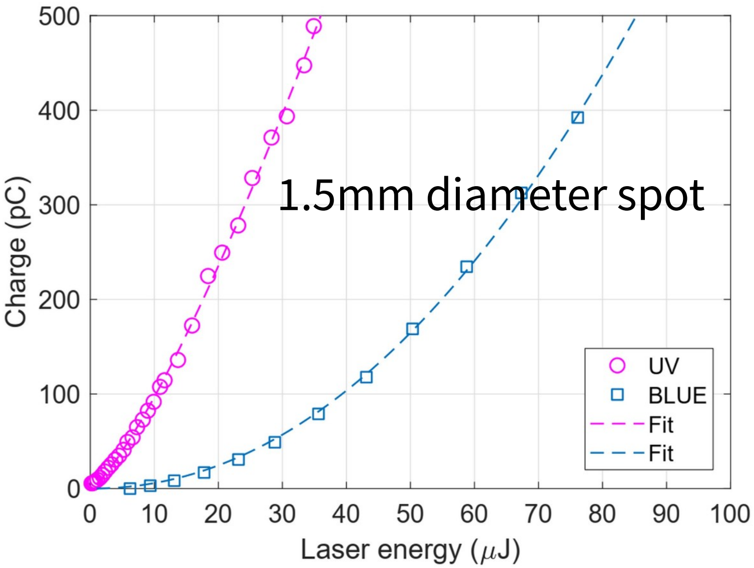
- *Measurements done with different laser energies and spot sizes on cathode*
- *Emittance comparison*

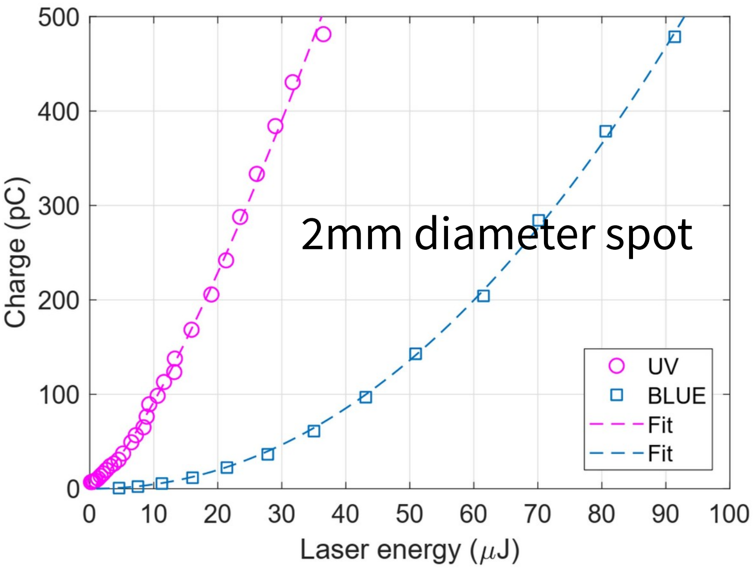


QE comparison

1mm diameter spot







Emittance comparison

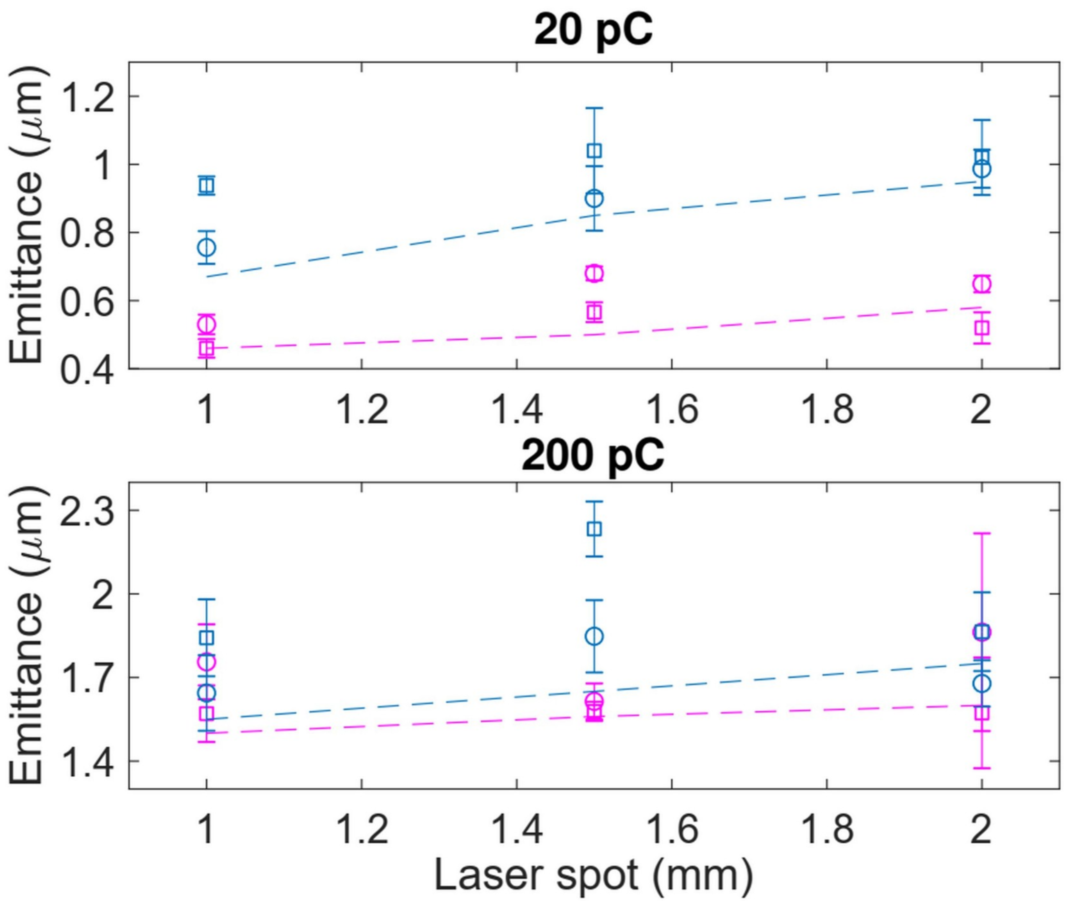
We compared the emittances when using UV and blue

Measurements done at low (20 pC) and high (200 pC) charge to show the effects of space-charge

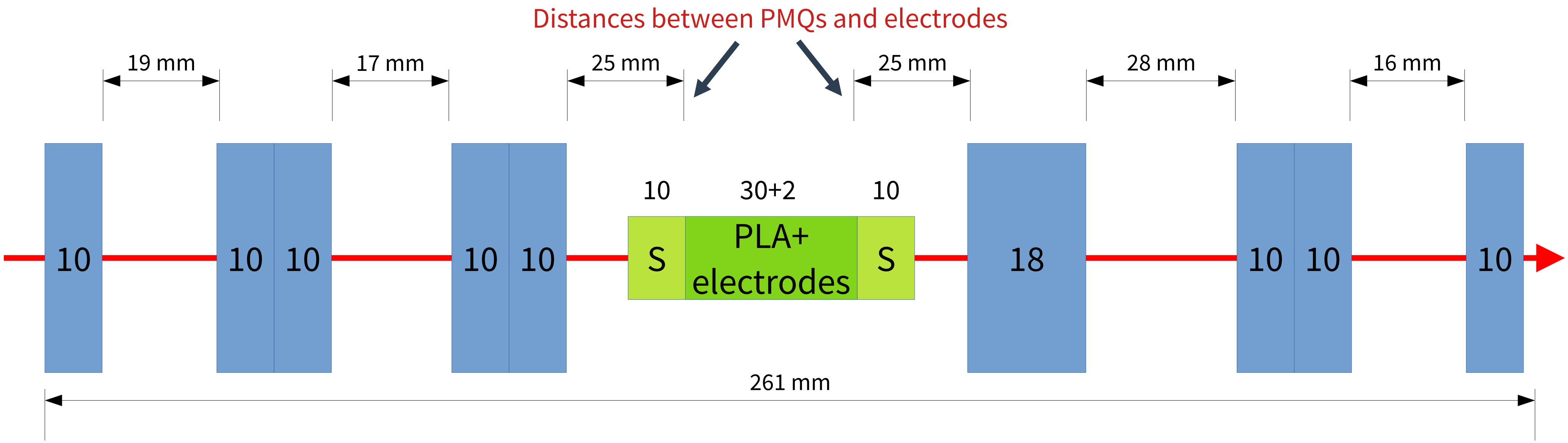
Conclusion: emittance obtained with UV is slightly smaller than the one with blue

Electrons are emitted with smaller kinetic energy when using UV (closer to copper working function)

Need to repeat the comparison to see the effects of cathode's aging

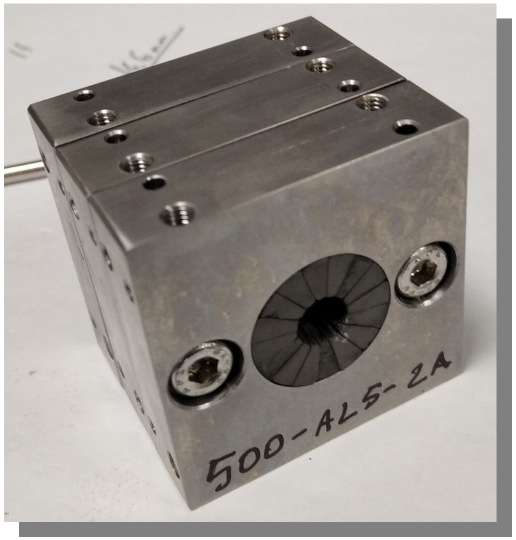


Tests with new PMQ setup (July 22)

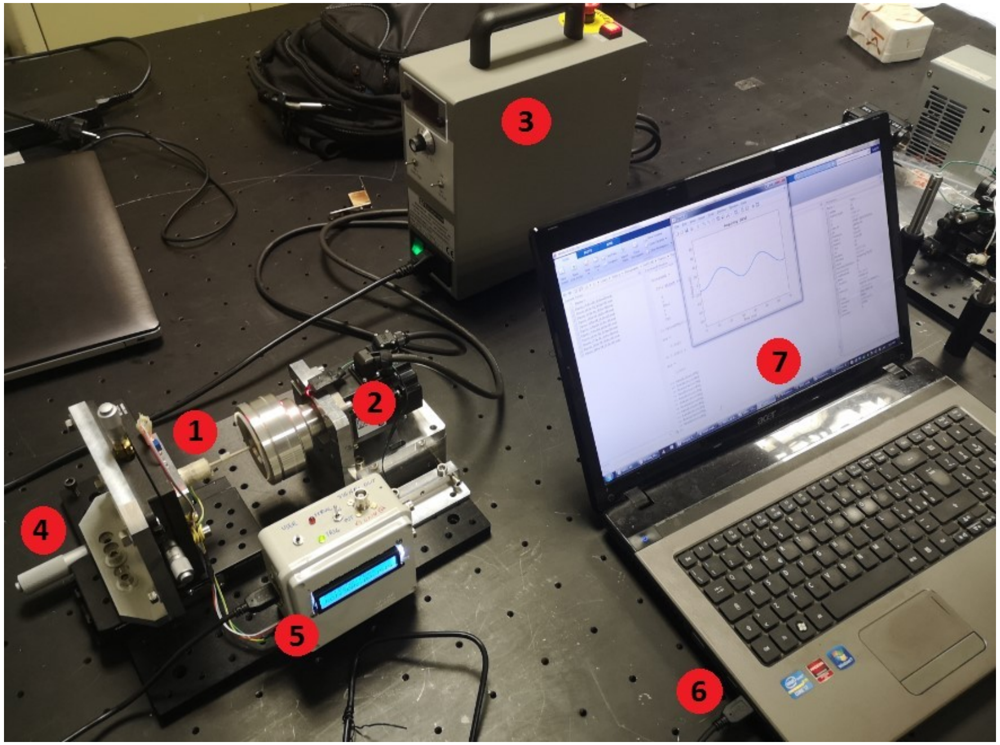


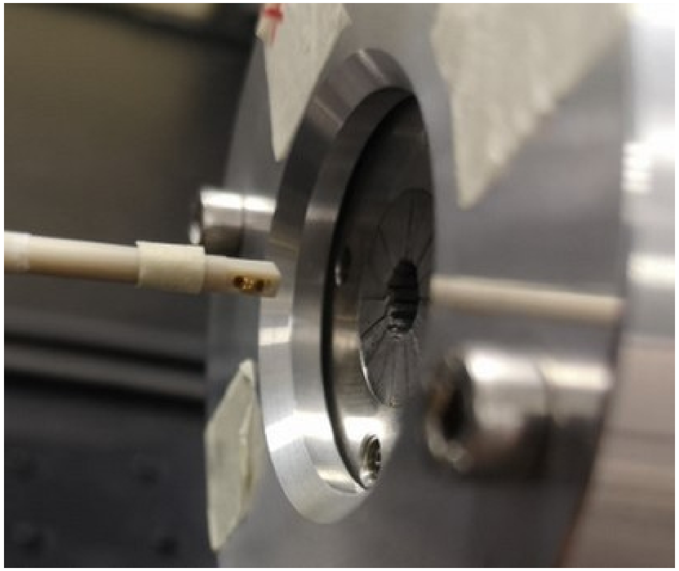
- PMQs should move by ±7 mm between them
- 500 T/m, r=3 mm, L=10,18,20 mm
- Obtained by merging single 10 mm pieces
- Currently available @ SPARC_LAB
  - *1xAL6+1xAL4 = 4x18 mm*
  - *2xAL5+2*AL3 = 8*10 mm*

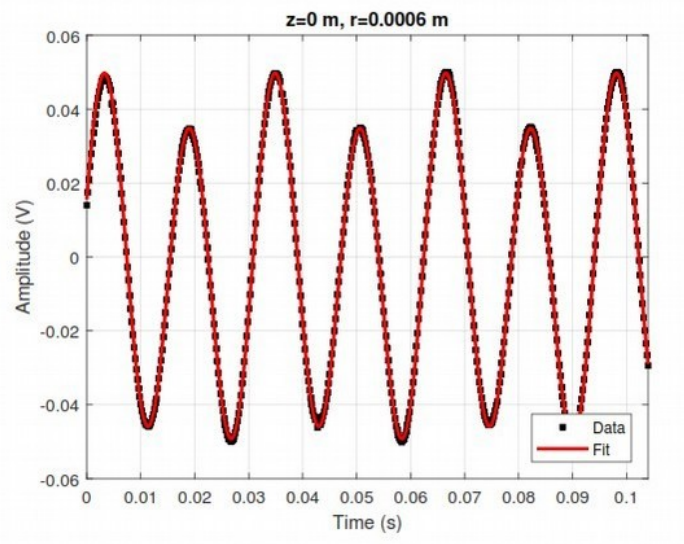
$$\beta_f = \frac{f^2}{\beta_i}$$



Characterization of the PMQs

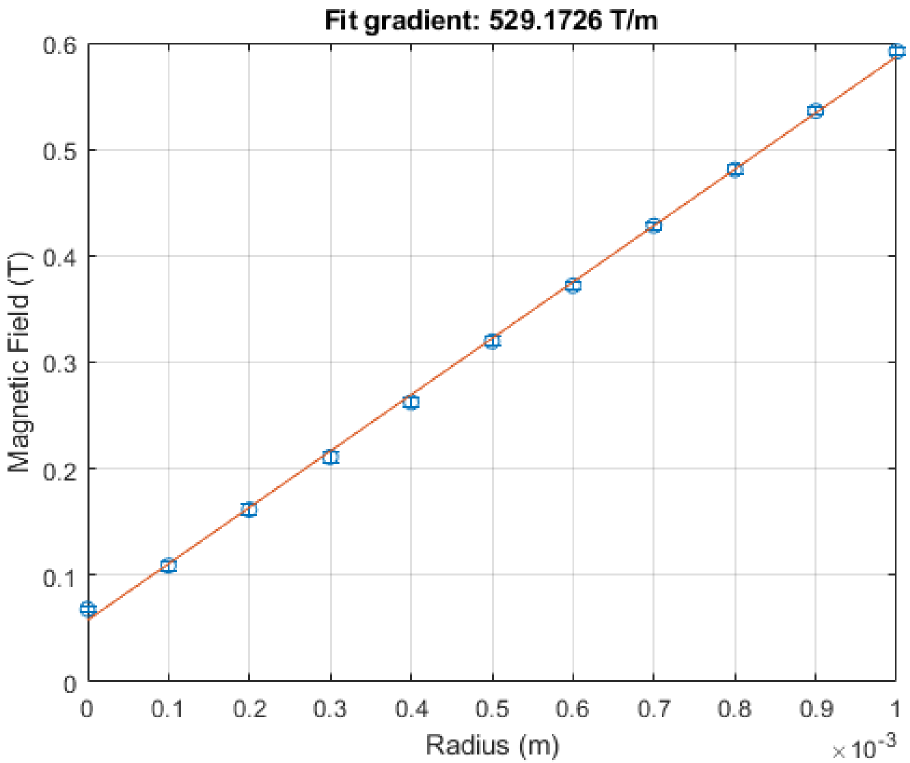






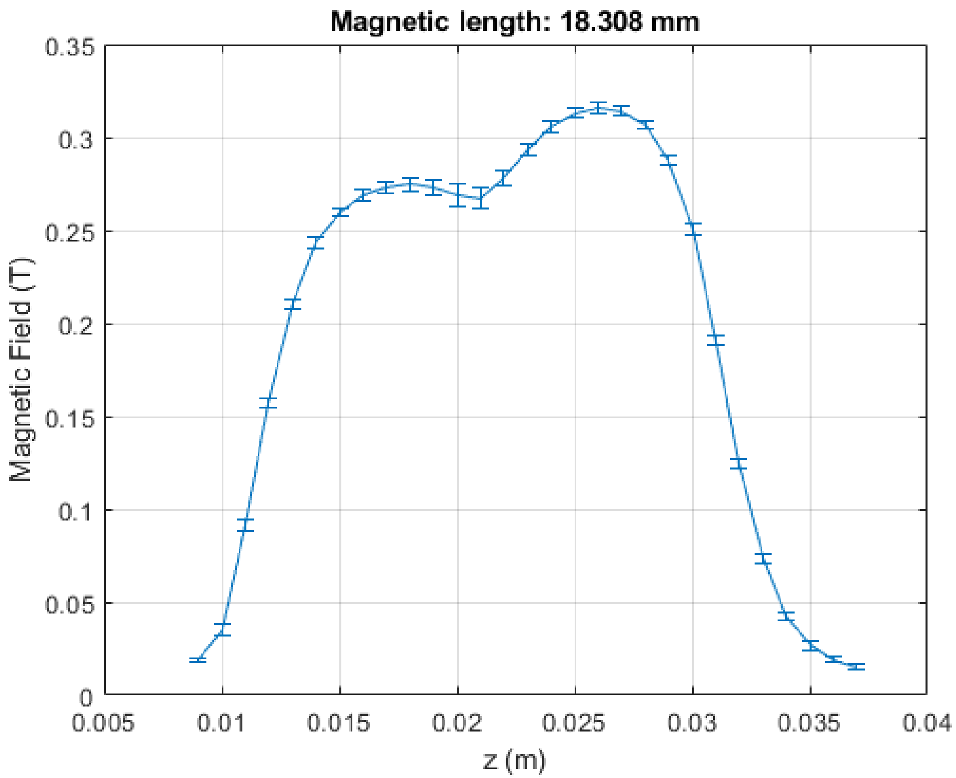
R Pompili, et al. Compact and tunable focusing device for plasma wakefield acceleration. Review of Scientific Instruments, 89(3):033302, 2018

Example of characterized PMQ



From KYMA

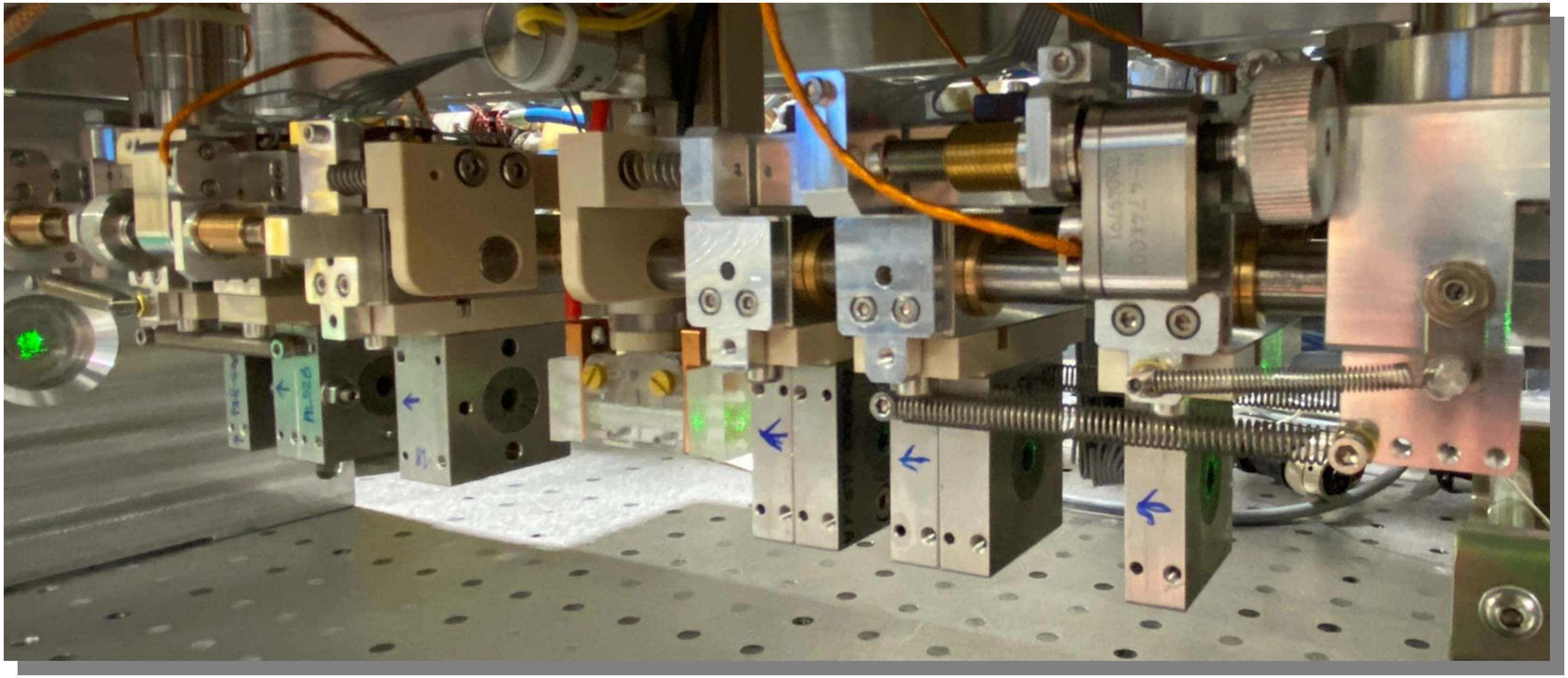
- 500 T/m
- 10+10 mm



Integrated field @ 0.5 mm

B*z=5.78 T*mm

PMQ setup tested in July



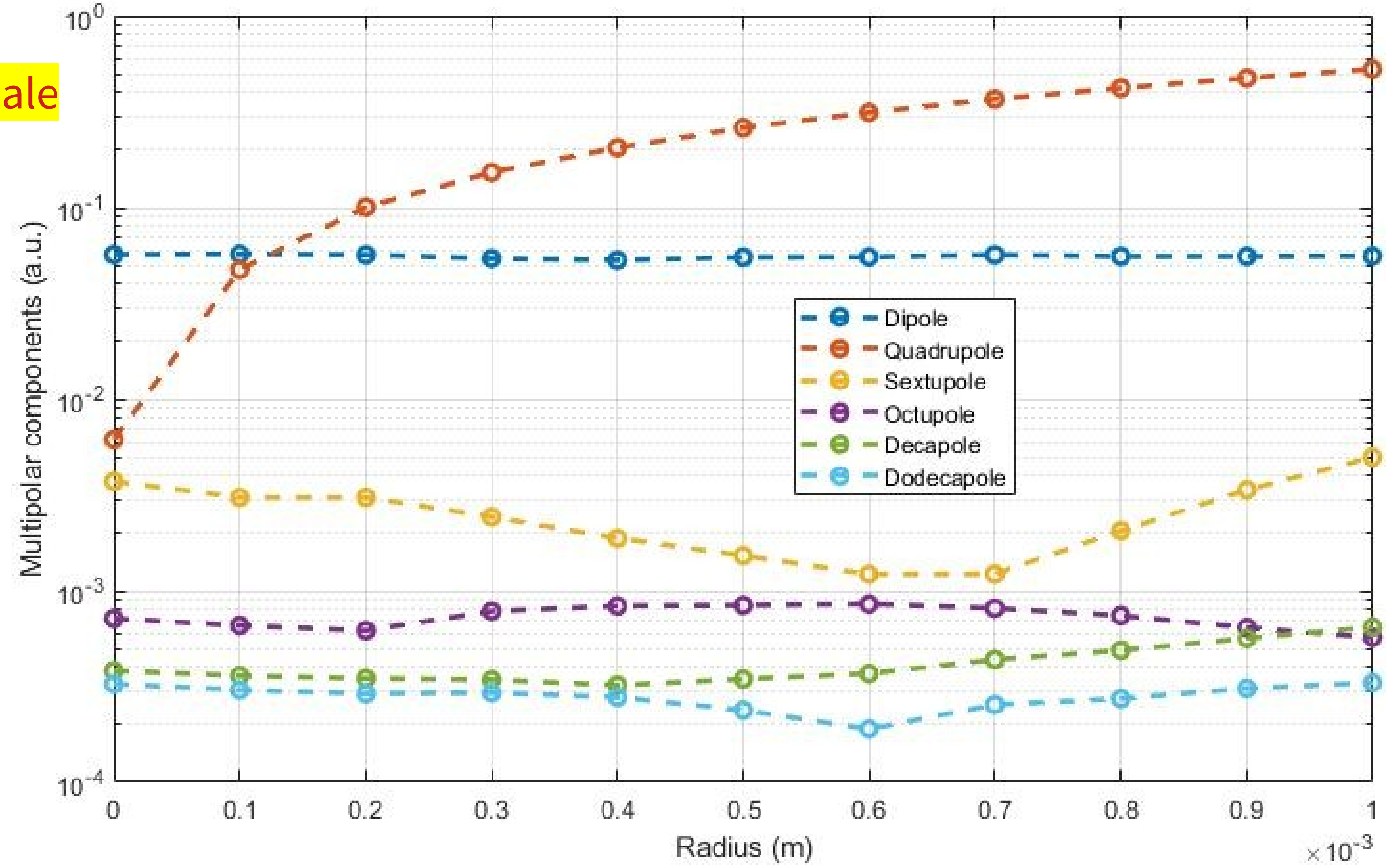
Simulations foresee beam waist of approx 4 um. Actually we measured 30-40 um minimum spots…

Even by introducing large misalignments (1-2 mm) between PMQs, the waist is below 10 um…

Entire system dismounted, measurements on going. For the current activities we moved back to the old system used for FEL run

PMQ multipolar components

Log scale



Toward GV/m accelerations

First results showed modest accelerations due to

- *Low charge (200 pC) of the driver bunch, mainly limited by the old RF gun and its low QE*
- *Low plasma density (10^{15} cm-3), mainly due to the limited witness transverse matching*

The goal is to increase the accelerating gradient while working at low plasma density (larger bubble size)

- *Driver charge increased to 500 pC, witness charge is 50 pC, same plasma density*

Enhance the witness properties, especially its density

- *Shorter duration with higher charge → enhanced beam-loading in plasma*

NB: simulations done using the new RF gun

Simulated longitudinal phase-space

Driver (20k macro-particles)

Duration: 150 fs (rms)

Emittance: 6 um (rms)

Spread: 0.5 MeV (rms)

Witness (20k macro-particles)

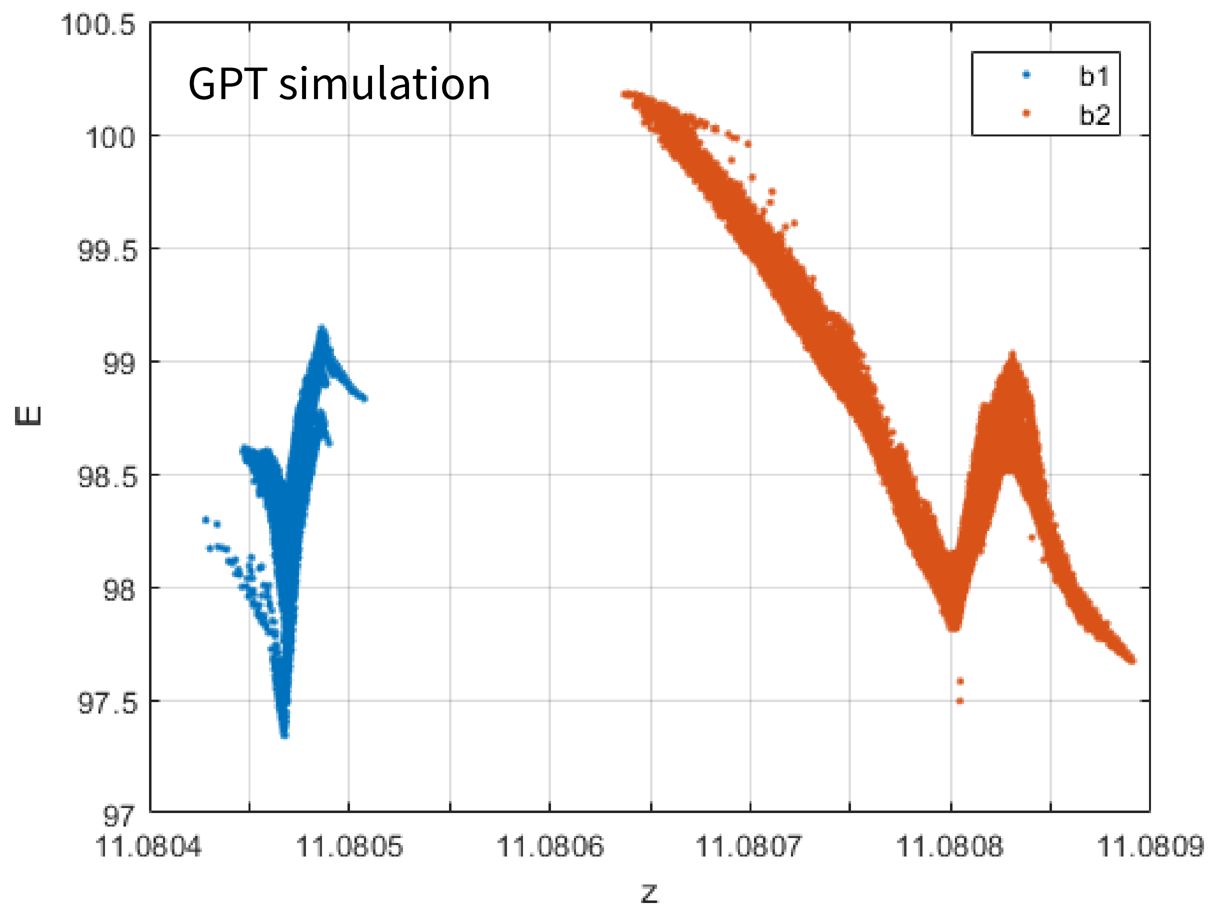
Duration: 19 fs (rms)

Emittance: 2 um (rms)

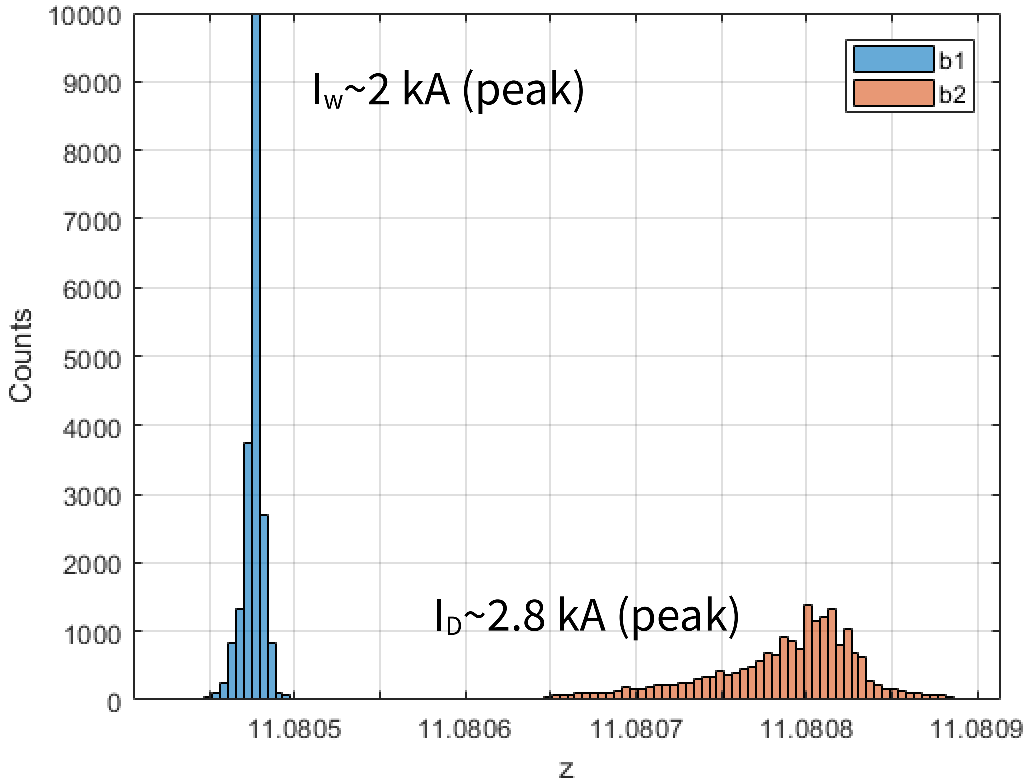
Spread: 0.25 MeV (rms)

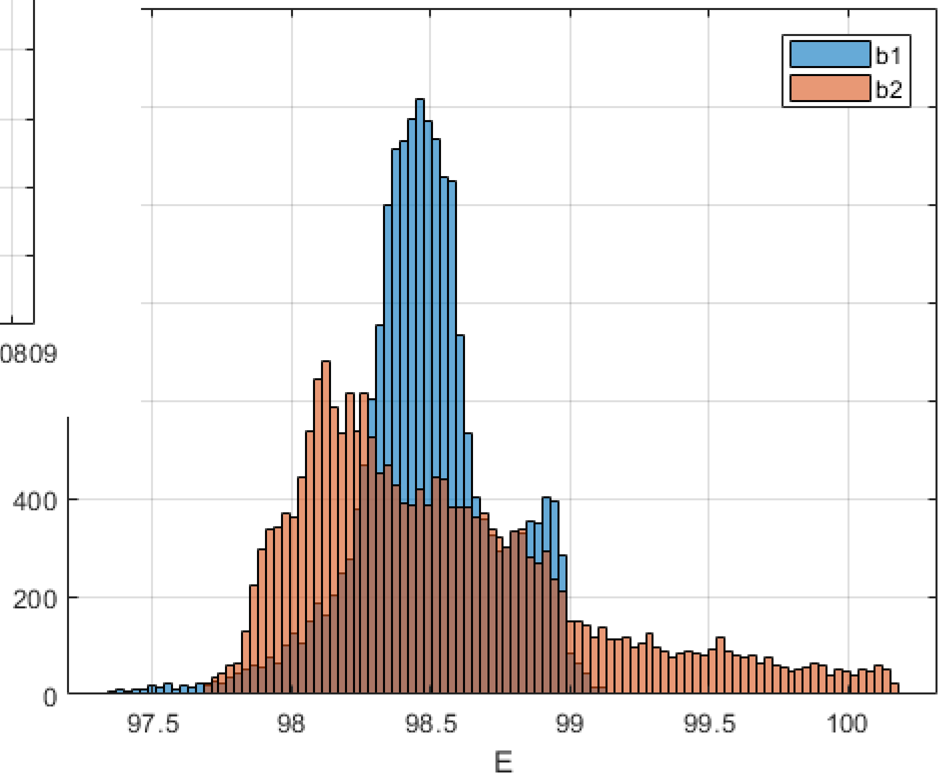
Distance

1.03 ps

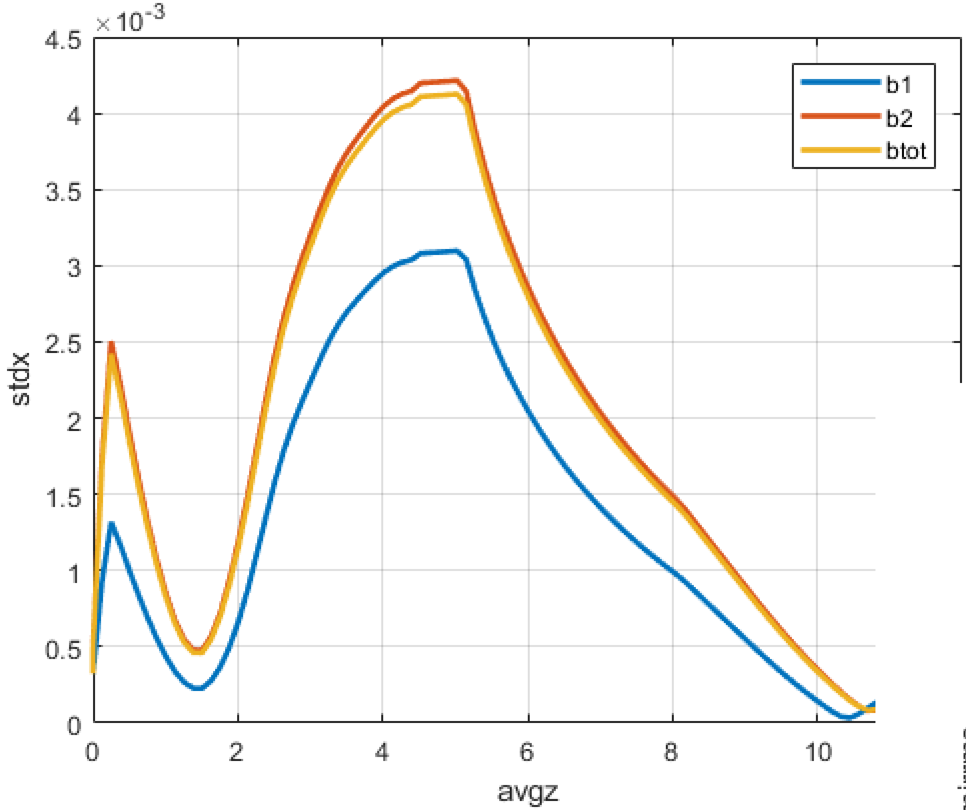


Histograms


10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Counts
I$_w$~2 kA (peak)
I$_D$~2.8 kA (peak)
b1
b2
11.0805
11.0806
11.0807
11.0808
11.0809
z

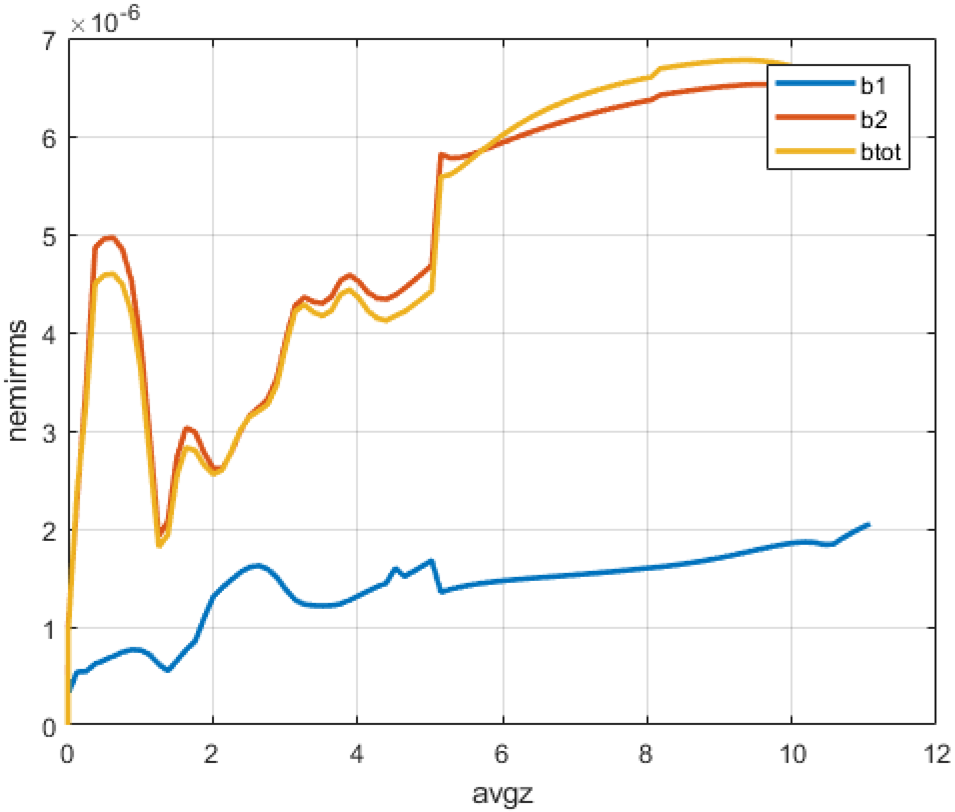

b1
b2
400
200
0
97.5
98
98.5
99
99.5
100
E

Envelope and emittance

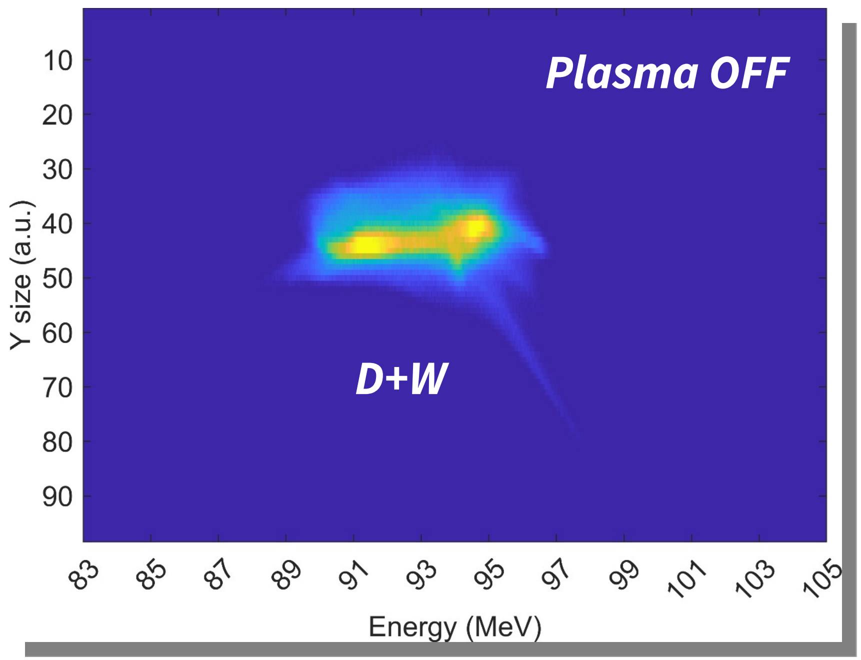


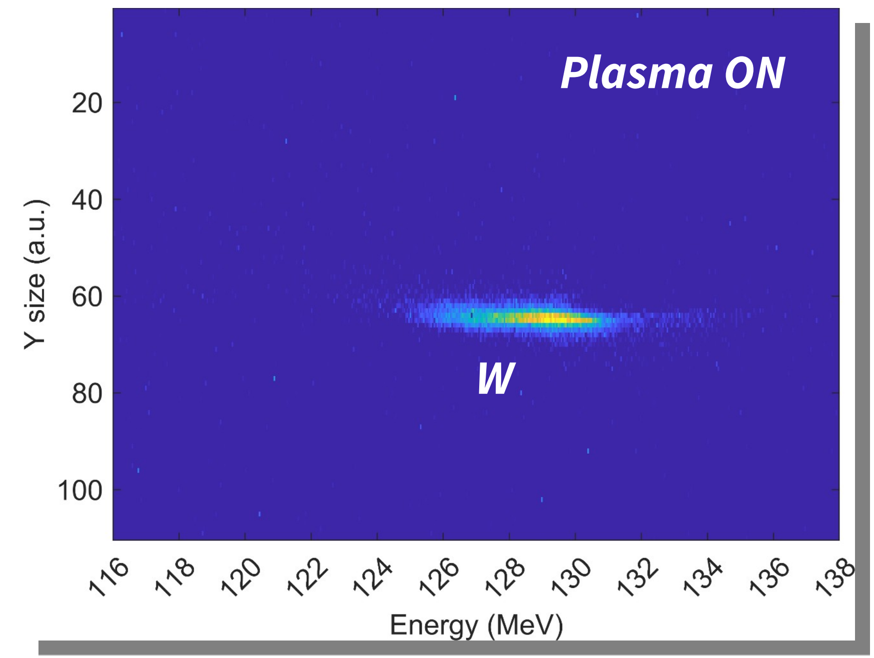
To achieve shorter witness duration with increased charge, the bunch is let expand transversely in S1. Than it is gradually caught by S2 and C3

Experimentally we found several issues related to the transverse phase-space of the compressed driver+witness. Therefore we slightly changed the setup to achieve better transverse space at expense of longer bunches



Latest acceleration results (Nov 2022)





3 weeks dedicated to optimization of acceleration results with 500+50pC WP

Measured accelerating gradients of the order of 1.2 GV/m

Only part of the witness is transported to the spectrometer (it cannot be quantified because also part of the driver is transported up to the BCMs)

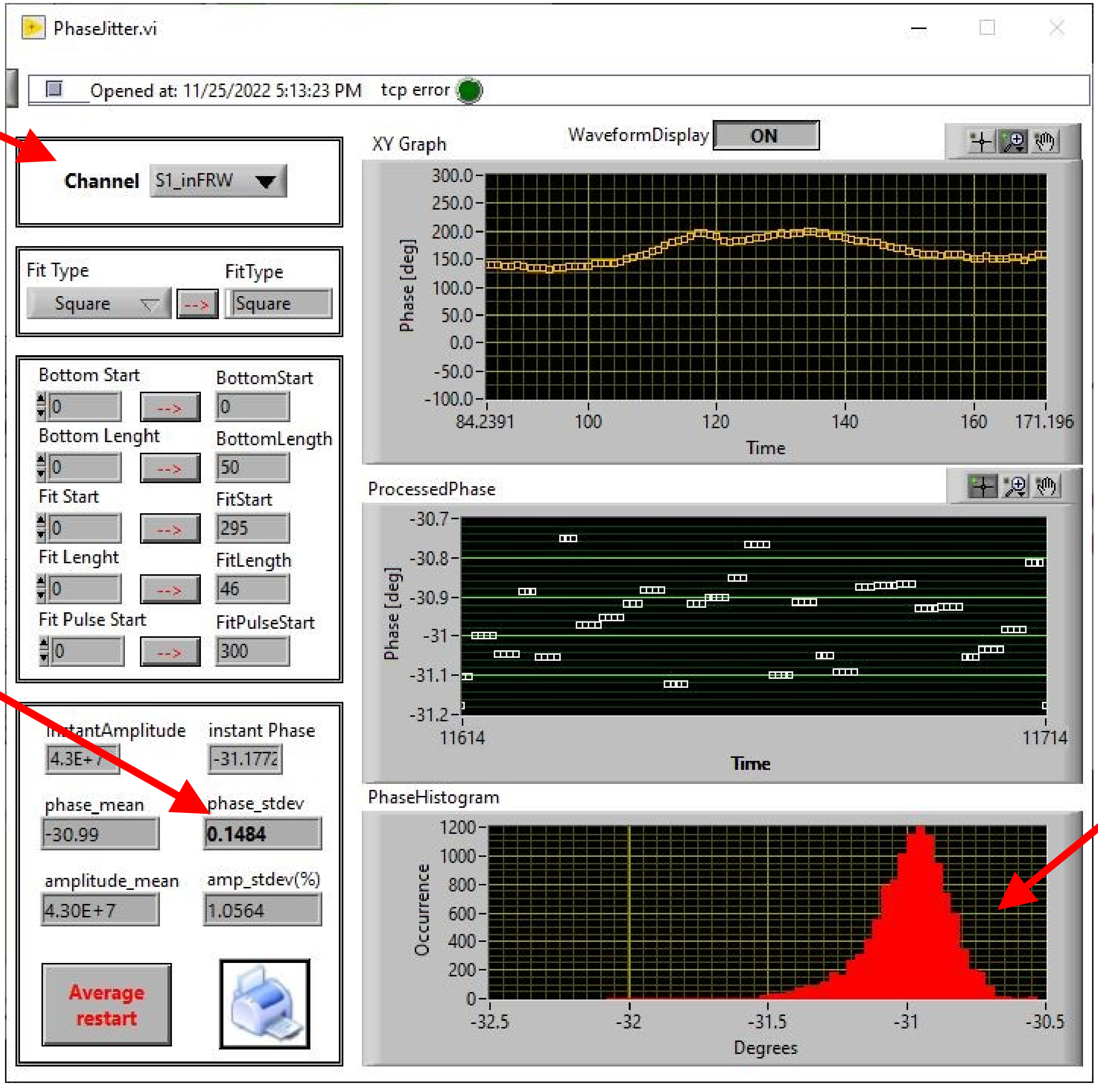
Unstable acceleration, probably due to large RF-to-laser jitter

Phase jitter

S1 (where VB is performed)

Jitter (in deg)

Jitter (distribution)



Electro-Optical Sampling diagnostics

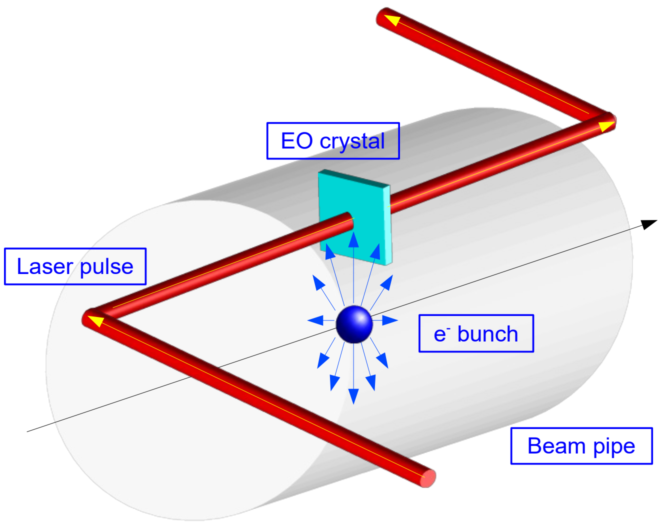
30° angle of the IR laser when impinges on the crystal (ZnTe, GaP)

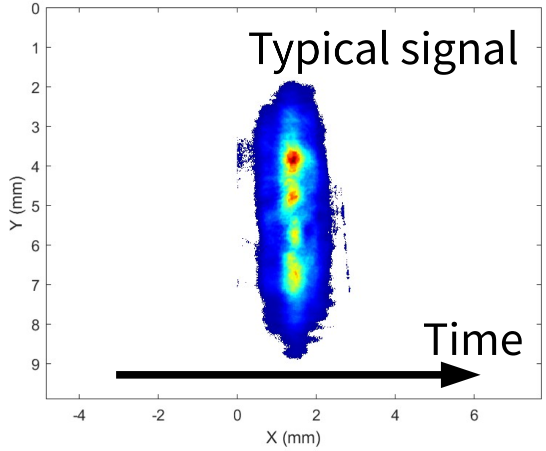
The signal is read by a CCD

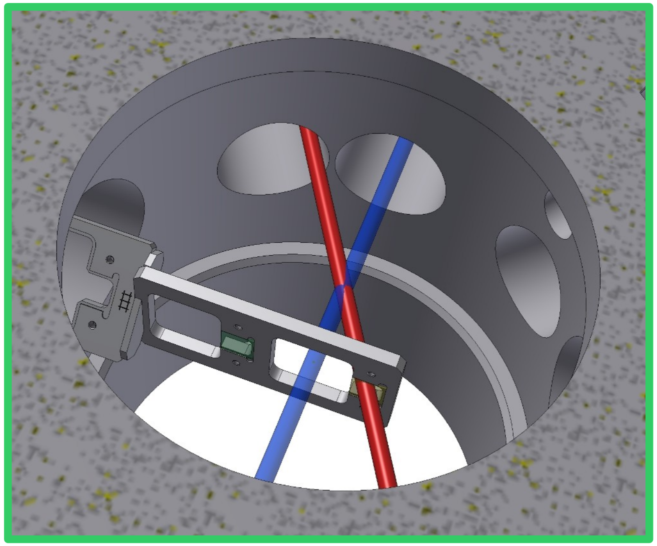
The spatial resolution is 19 fs/pixel

IR laser monitored with a fast Hamamatsu photo-diode

A 300 mm delay line is used to sync the IR laser and the electron bunch







Jitter results

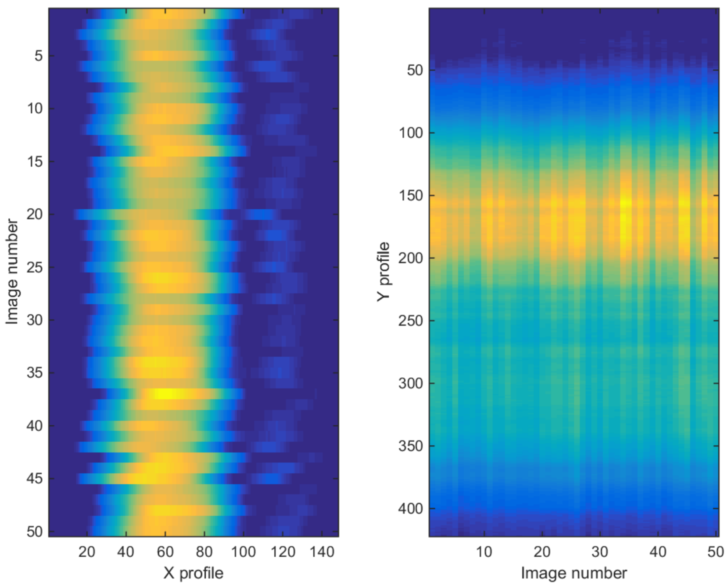
ID	Pos(ps)	RMS(ps)	Err(ps)	Q(%)	Err(%)	**Jitter(ps)**
1	5.291	0.279	0.007	94.458	7.030	0.051
2	6.334	0.133	0.024	5.542	12.246	0.046
All	5.294	0.296	0.010	100.000	7.231	0.049

Intra-bunch jitter mainly due to S1 RF jitter (where velocity-bunching is performed). Laser-to-RF now is 50 fs, and cannot be further optimized without important changes (modulators, wave-guides, etc.)

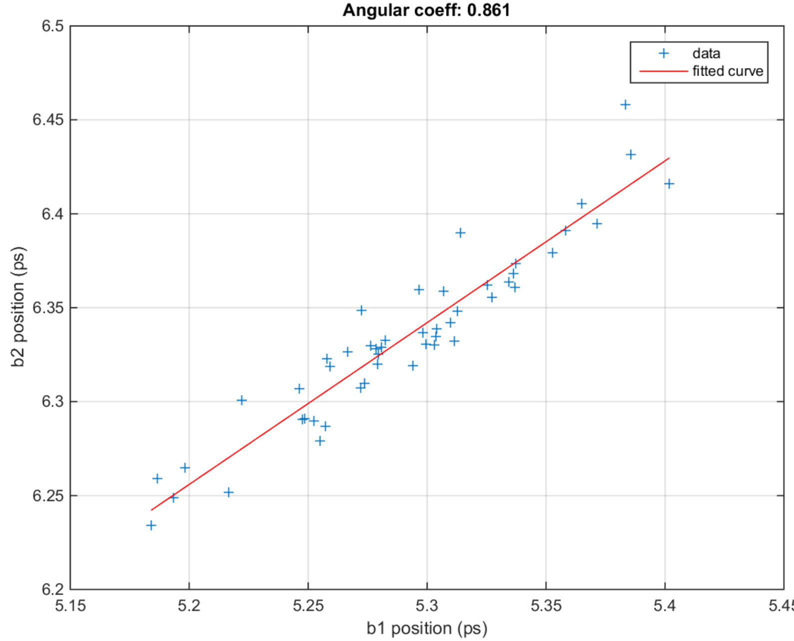
Dist(ps)	Err(ps)
1.043	**0.019 (up to 40 fs)**

Bunch 1 vs bunch 2

Laser vs bunch



Time →



Conclusions

Important progress has been achieved with plasma acceleration in view of EuPRAXIA

- *Accelerations up to 1.2 GV/m were achieved and confirmed over 3 weeks of run*
- *Clear indication that the increase of the driver charge strongly pushes the accelerating field*
- *No deterioration of results observed over 2 months of run using a sapphire capillary*

Some issues still remain

- *Transverse spot size at PMQ entrance not optimized due to misalignments of S1 solenoids (will be replaced next year by SABINA)*
- *Witness transverse matching limited by PMQ nonlinearities*
- *Unstable witness acceleration due to RF-to-laser jitter*

Next steps

- *Test of alternative plasma ignition with laser filaments (toward high repetition rates)*
- *Test with active-plasma lens as possible alternative to PMQs*
- *Need to reduce as much as possible the RF jitter (new solid state modulator? New waveguides?)*