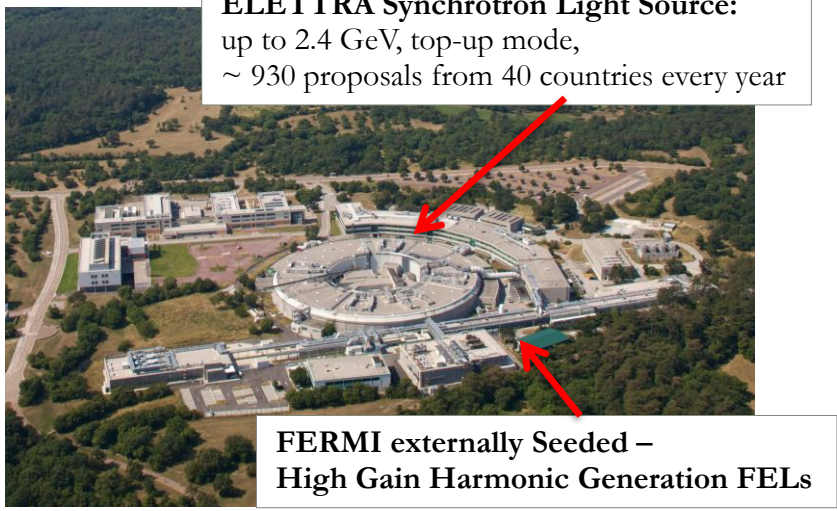
Elettra
Sincrotrone
Trieste

Two-bunch operation with ns temporal separation at FERMI

Giuseppe Penco

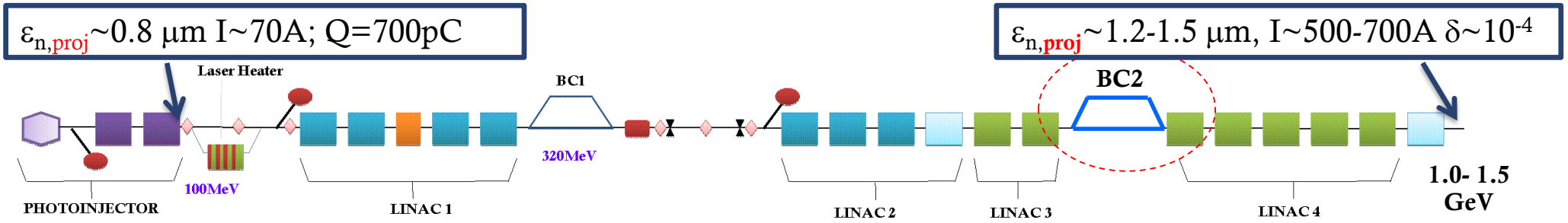
On behalf of the FERMI Physics Team

Outline



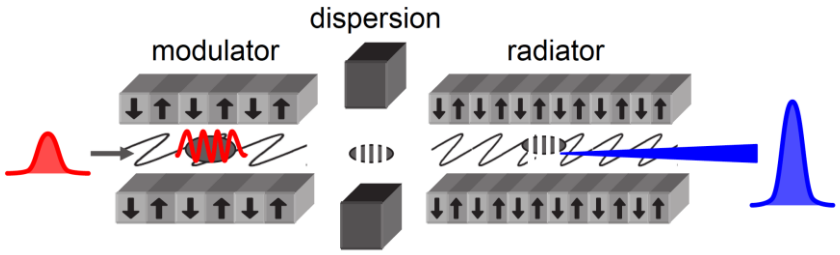
- Introduction:
  - FERMI in a nutshell
  - Overview on two-color schemes
- Two-bunch generation and transport along the FERMI linac
- Longitudinal phase space manipulation
- Lasing in two-bunch mode on FEL-1 (XUV range)

FERMI Linac



- S-band (~3GHz) normal conducting linac with a 10-50Hz rep rate;
- Nominal operation with only one bunch compressor (but two-stage compressor is an open option);
- Accelerating sections:
  - Travelling Wave in the photoinjector, Linac 1 (+X-band) and Linac 2
  - Backward Travelling Wave (high impedance) in Linac 3 and Linac 4 (strong geometric Wakefields to deal with)

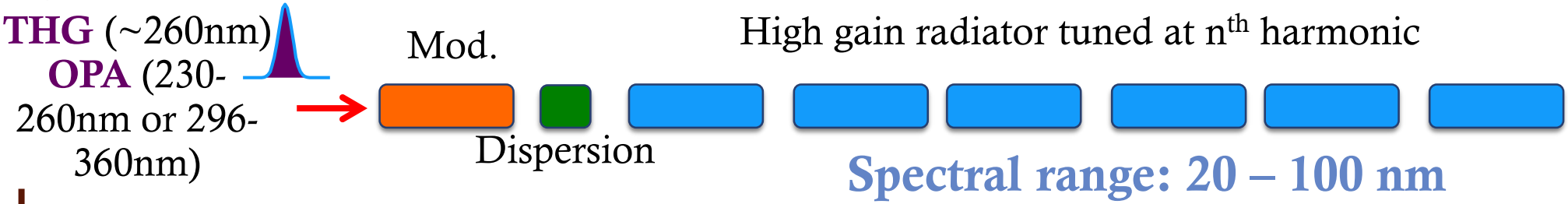
FERMI (High Gain Harmonic Generation): FEL-1 and FEL-2



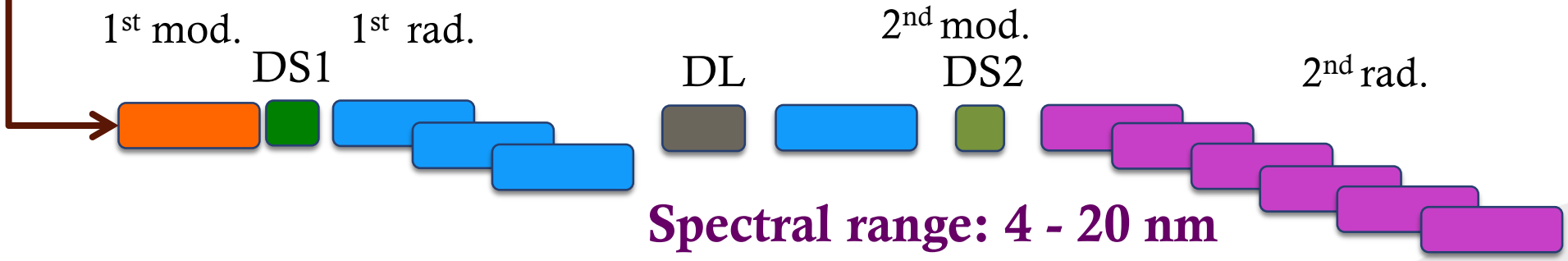
FEL-1 : Single stage HGHG

* Apple II type helical undulators (variable gap)

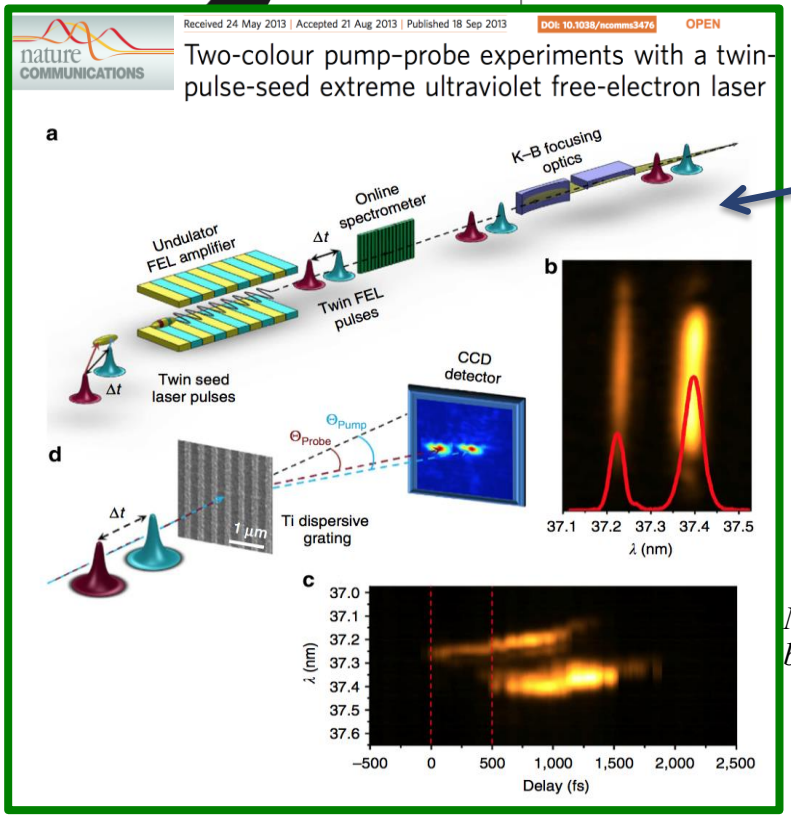
Seed Laser:
THG (~260nm)
OPA (230-260nm or 296-360nm)



FEL-2 : Double stage HGHG with fresh bunch injection technique

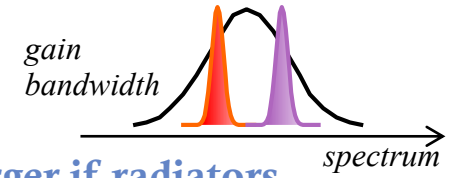


FEL-1: multi-color operation



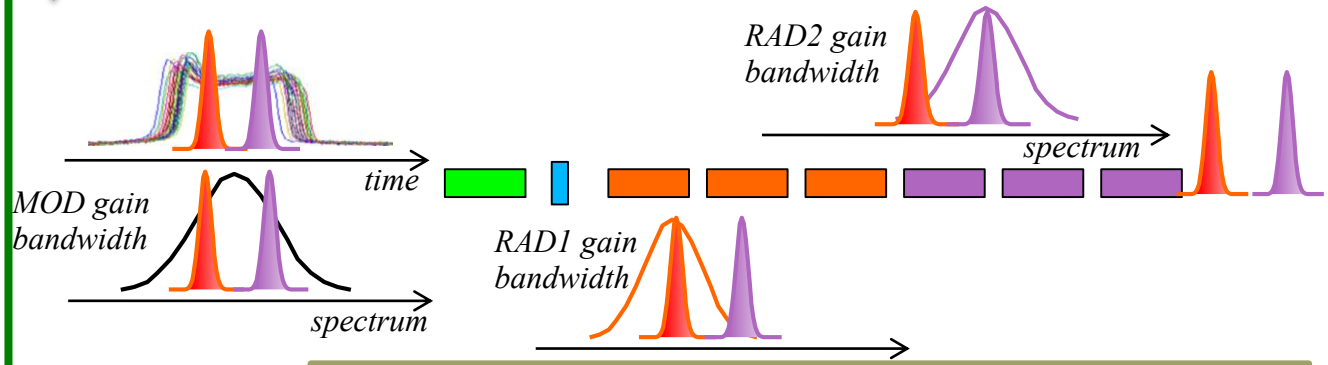
- Two seed lasers on the same electron bunch, with a ΔT from 200fs to 700-800fs:

A) FEL Spectral separation 0.4-0.7%

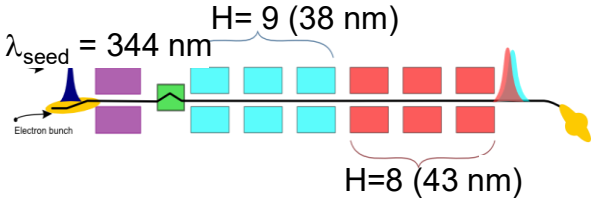


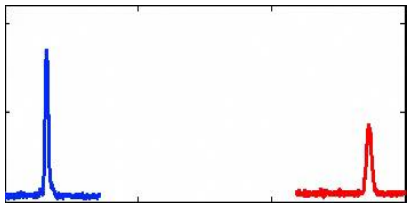
B) FEL Spectral separation 2-3% or larger if radiators are tuned at different harmonics

Ferrari et al., Nat. Comm, 2016



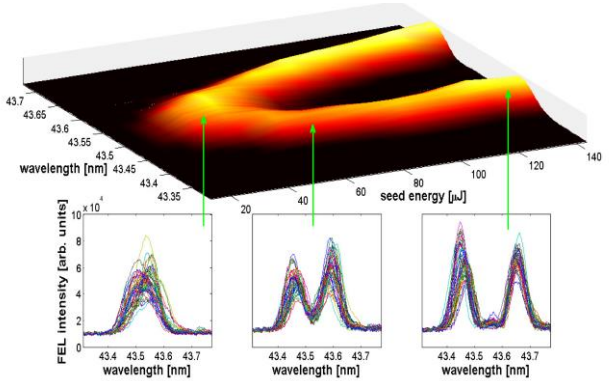
- Simultaneous FEL pulses with large (>10%) λ separation using single seed with undulators at two harmonics





- Pulse Splitting by using a powerful chirped Seed Laser

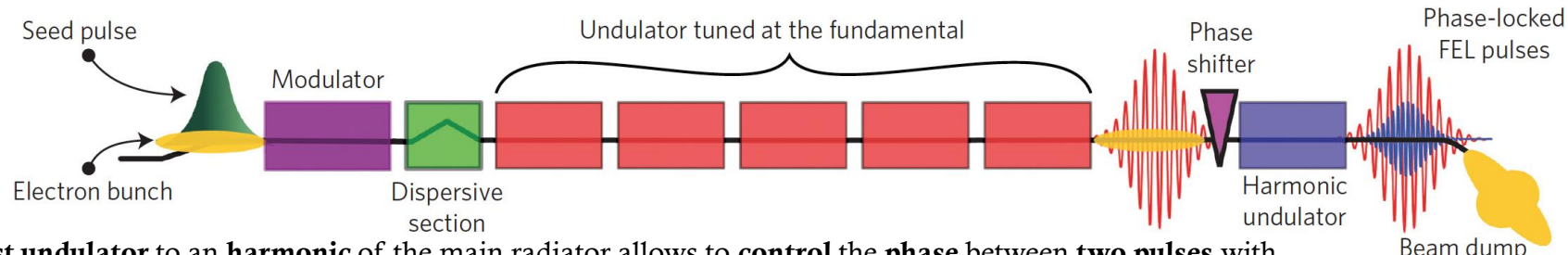
PRL 110, 064801 (2013)



Optics Express 21, 022728 (2013).

FEL-1: multi-color, coherent control

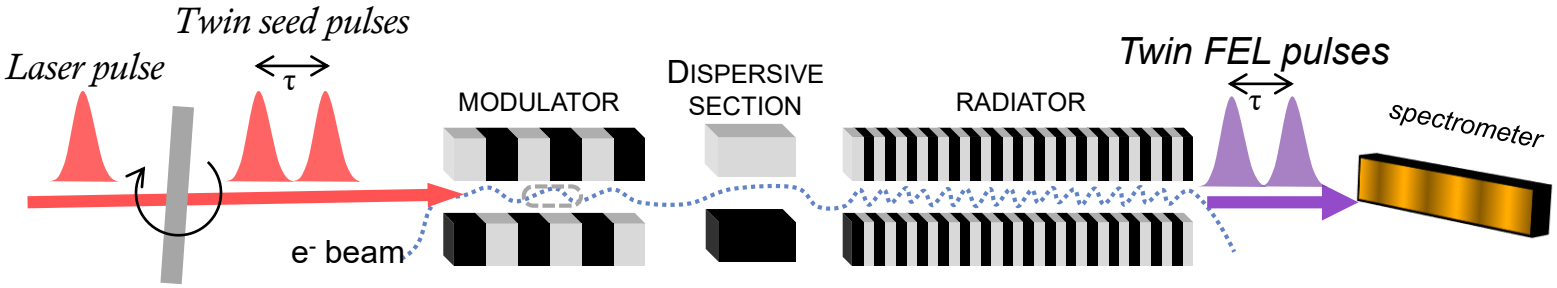
LETTERS NATURE PHOTONICS DOI: 10.1038/NPHOTON.2016.13

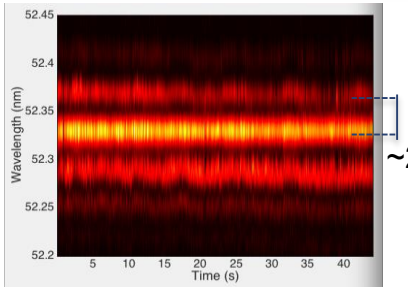


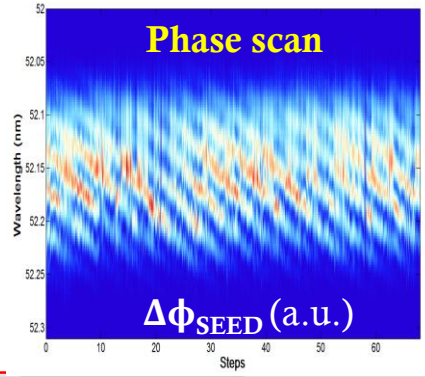
Tuning the **last undulator** to an **harmonic** of the main radiator allows to **control** the **phase** between **two pulses** with **different wavelength** (with a temporal resolution of **3 attoseconds**).

PRL 116, 024801 (2016) PHYSICAL REVIEW LETTERS week ending 15 JANUARY 2016

Generation of Phase-Locked Pulses from a Seeded Free-Electron Laser







Two time-delayed seed pulses are created by transmission of a single laser pulse through a **birefringent plate**. For **coherent pulses**, a fine tuning allows to control the relative phase $\Delta\phi_{seed}$

Interference between two **coherent** and **phase-locked** pulses is evident in the spectral domain.

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Time-scale in physical, chemical and bio-chemical processes

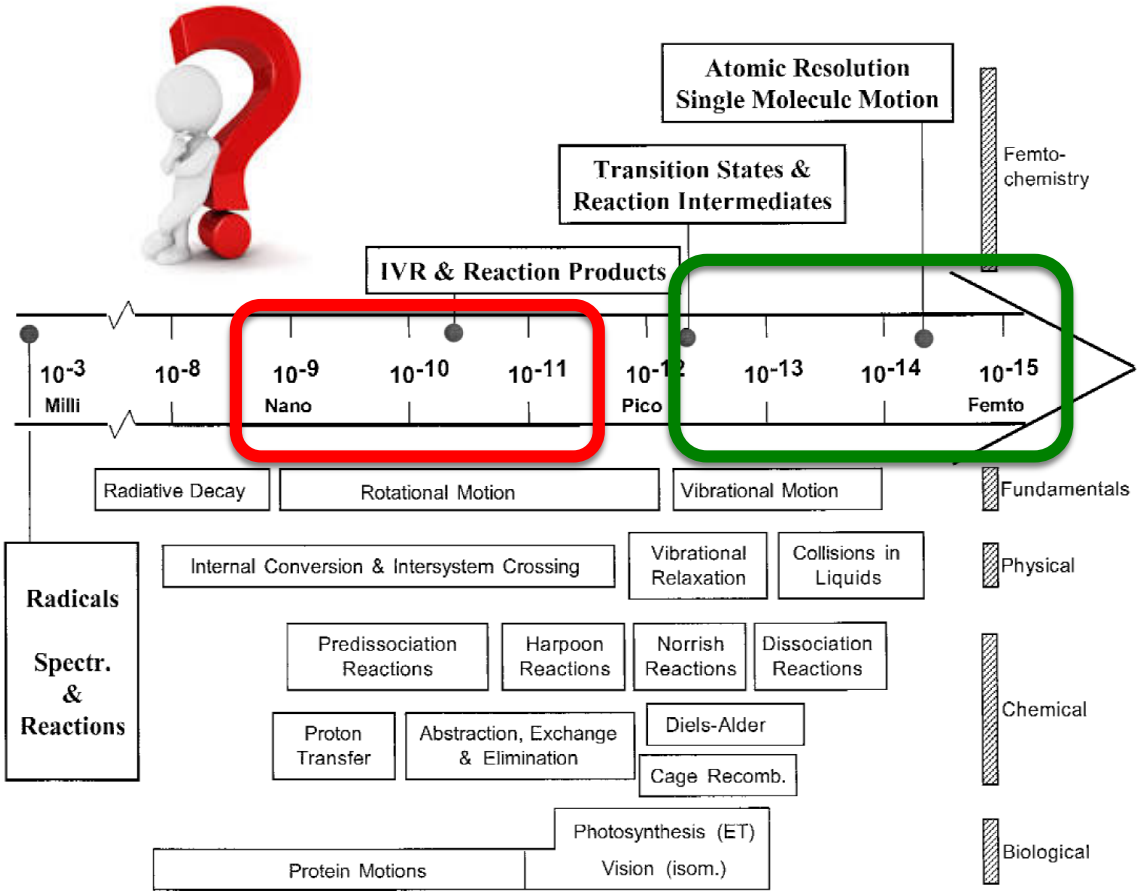


Fig. 1 Timescales. The relevance to physical, chemical, and biological changes. The fundamental limit of the vibrational motion defines the regime for femtochemistry. Examples are given for each change and scale.

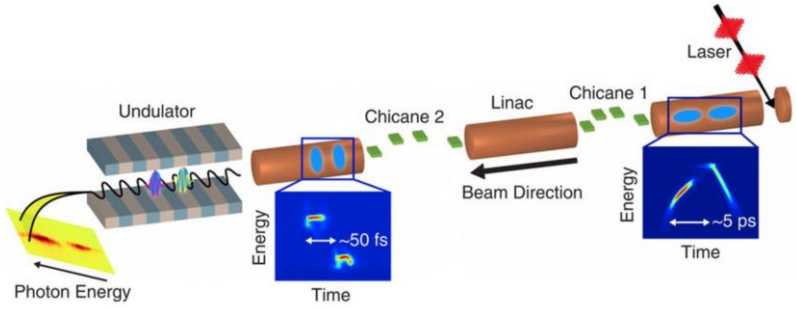
A.W. Zewail © 2000 IUPAC, *Pure and Applied Chemistry* 72, 2219–2231

Two-color schemes based on using:

a. Two portions of the same electron bunch.

a. Two independent electron bunch in the same rf-bucket

A.Marinelli et al. Nat. Comm. 6, 6369 (2015)



A photon delay-line can in principle extend the temporal separation, but at the cost of a significant pulse energy loss and of reduced flexibility, e.g. limiting the operation to a set of predetermined wavelengths.
W. Roseker et al., JSR 18, 481 (2011)

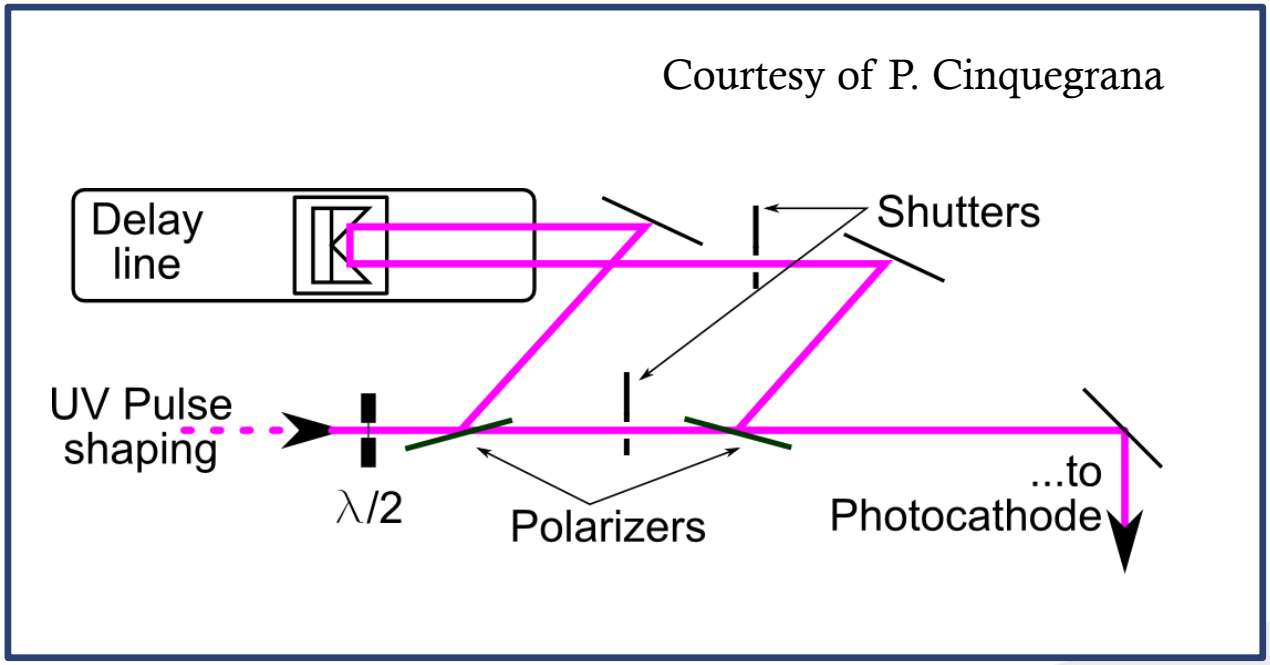
Two-bunch mode (ΔT~ns)

- **Generate two electron bunches at the gun separated by few main RF buckets** (i.e. multiple of 0.33ns)
- Common linac setting (trajectory steering, compression setting, feedbacks, …)

Photoinjector setup

- Gaussian temporal profile (FWHM~6.5ps)
- The UV pulse is splitted according to the polarization: one can be delayed from 600ps to 2.5ns
- Rotating a half-wave plate before splitting we can distribute the total laser energy between the two pulses
- Each PIL pulse has an independent shutter
- Laser Heater over both bunches

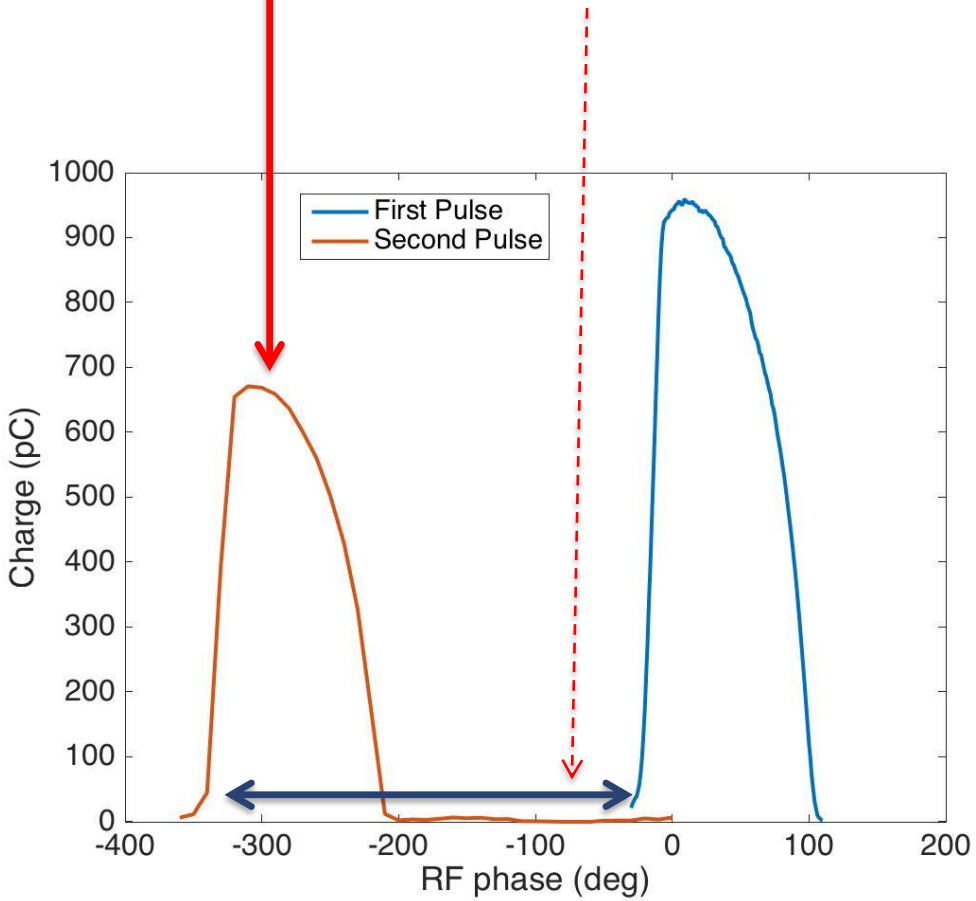
Ref.: Miltcho Danailov

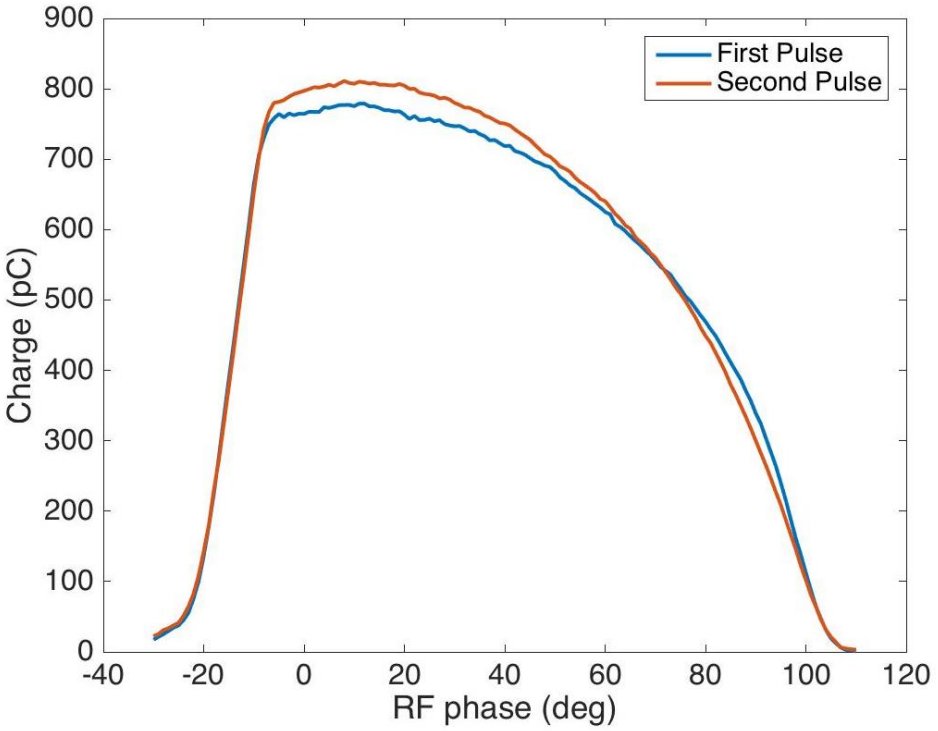


First Step: generate two identical e-beam

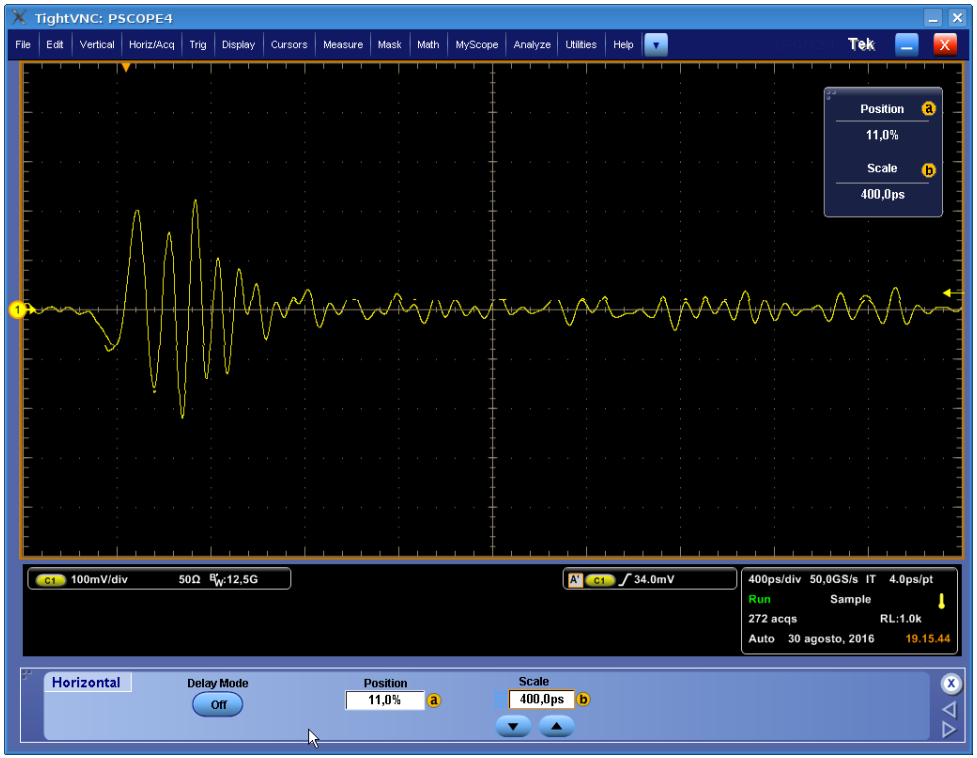
The Schottky Scan (Extracted charge vs RF gun phase):

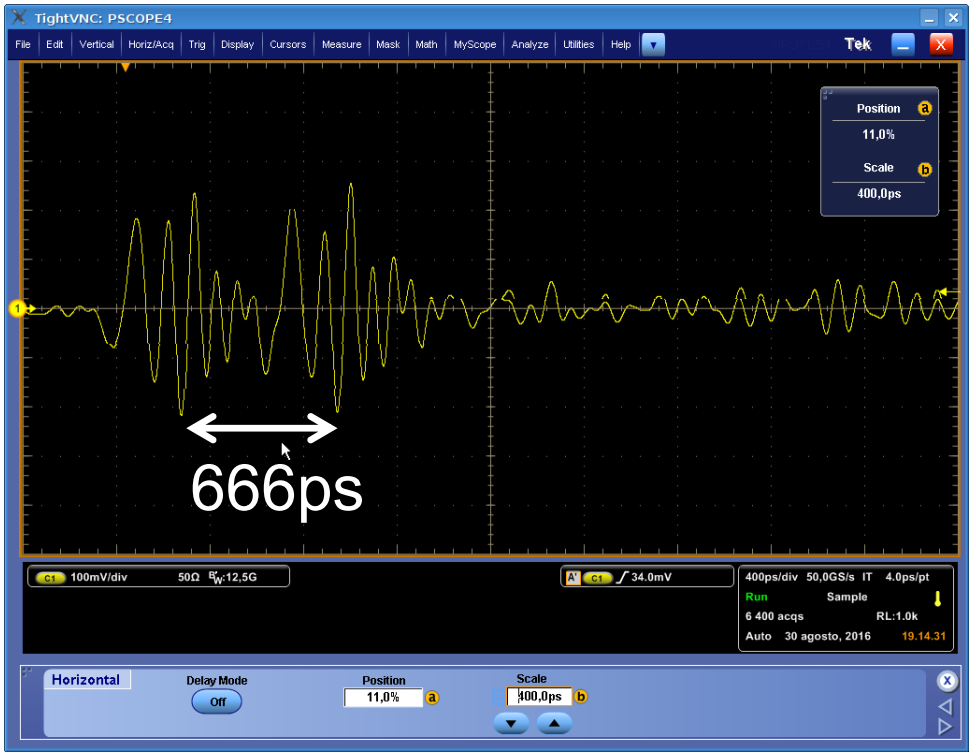
- The maximum charge extracted depends upon the energy distribution between the two pulses
- The zero-charge phase depends upon the delay between the two pulses





The two bunches detected by a scope on the Bunch Arrival Monitor after the injector (~100MeV)

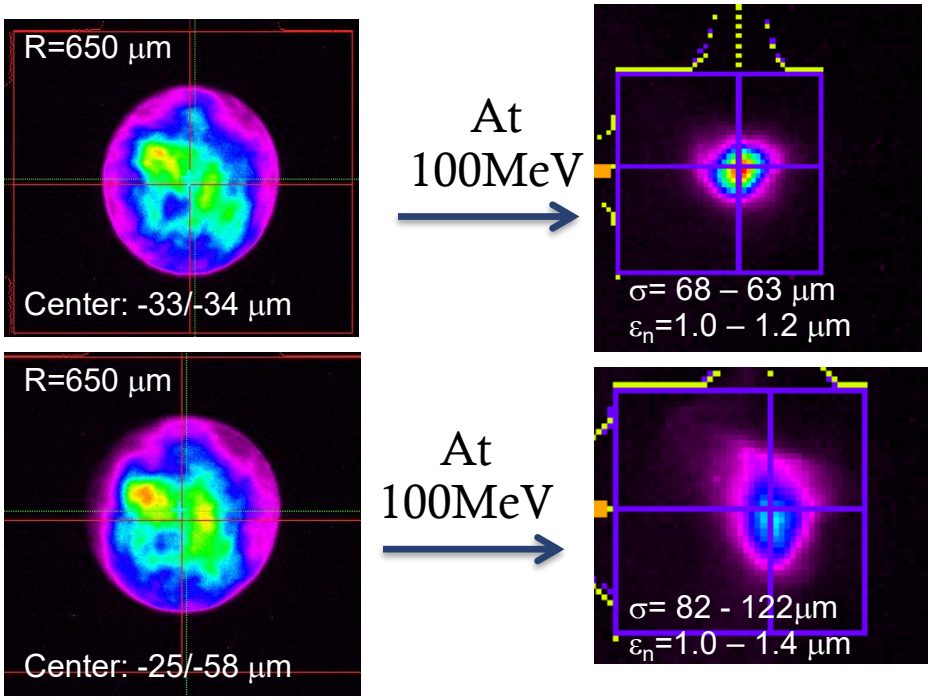




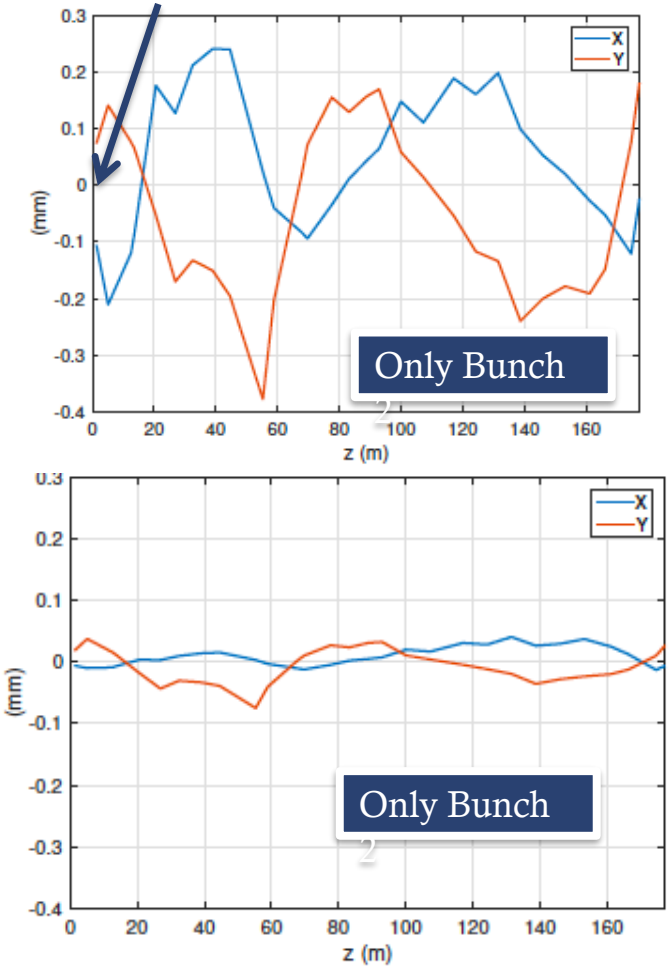
Courtesy of F. Rossi

Second step: verify they are similar in single-bunch

- Virtual Cathode Image: the two pulses are slightly misaligned



Using the **first bunch trajectory** and **disabling the Feedback**, the second bunch undergoes through a different trajectory already outside the gun

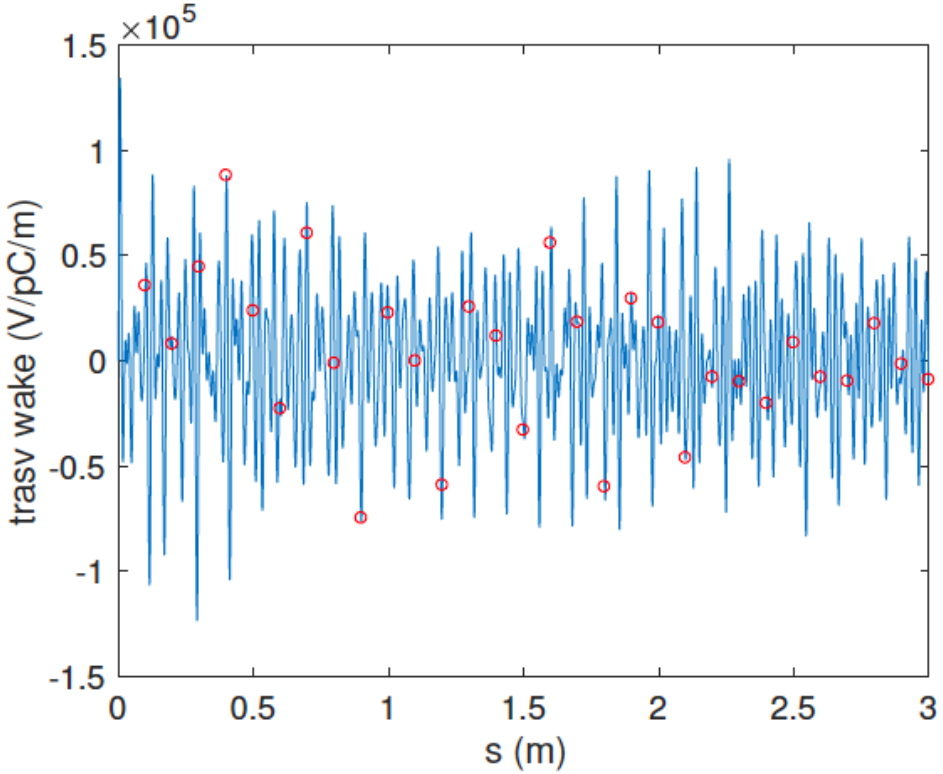


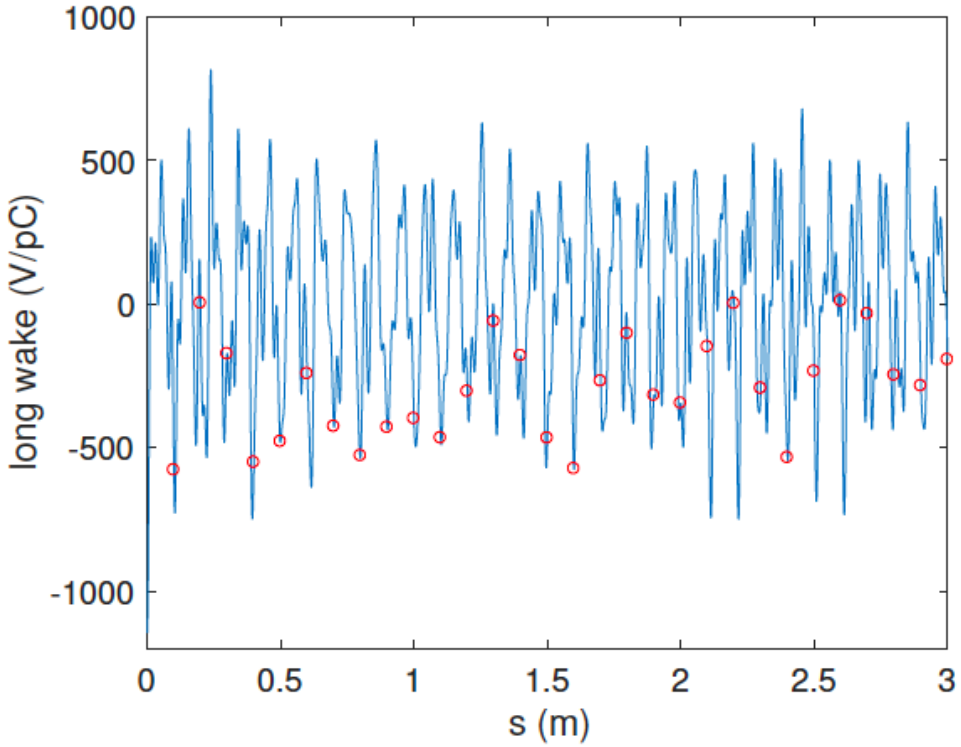
Adjusting the second pulse on the cathode (tens of μm) to have no trajectory steering after the gun:

- The two beam in LH and after BC1 look very similar and the traj of the second one alone is much more on-axis

Long-Range Wake Potential in BTW sections

Calculated with ECHO code and MAFIA (Ref. P. Craievich et al. Tech Note ST/M-04/02)

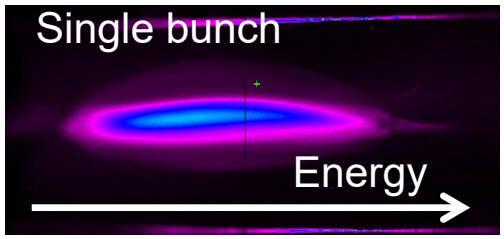


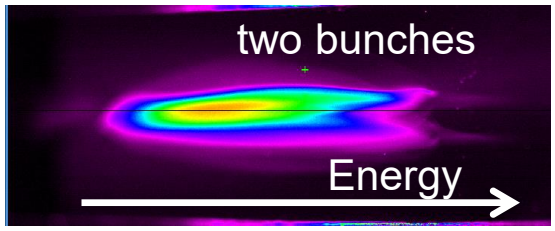


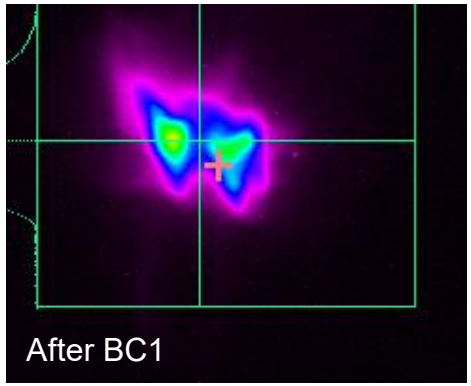
Red circles correspond to long-range wakes sampled by bunches in subsequent RF buckets

Two-bunch mode: linac transport

Screen in the mid of the BC1 chicane: the two bunches have almost the same energy:



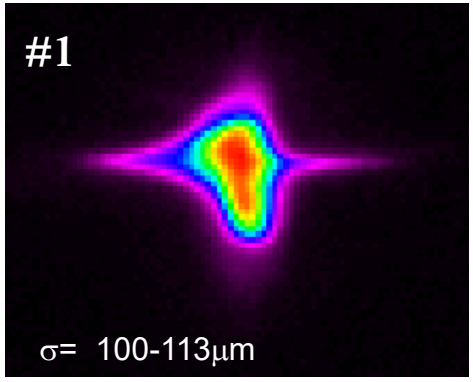


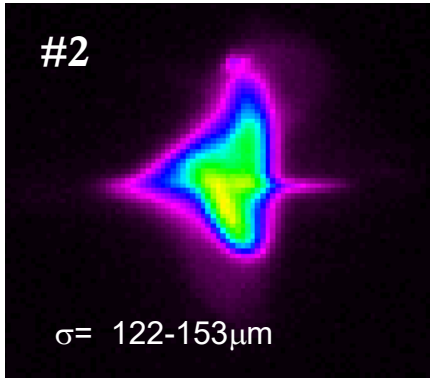


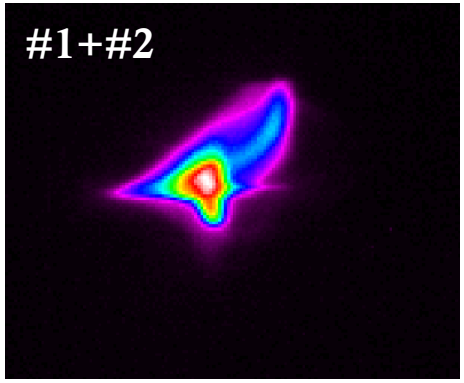
In TLS (end of the linac)

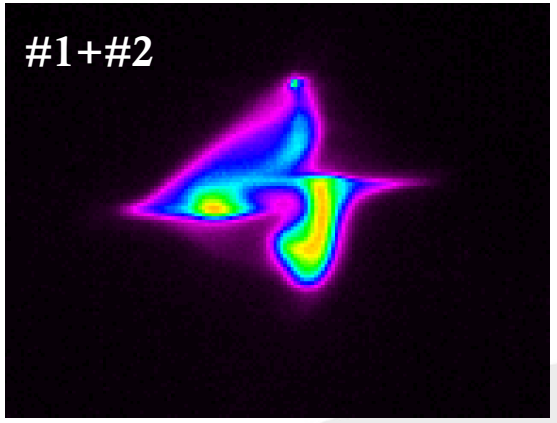
Traj. Feedback ON with only bunch #1, then in stand-by with only bunch #2 and in Two-Bunch mode

Activate a Traj. Optimizer (Ref. G. Gaio) to minimize the spot size on the TLS screen





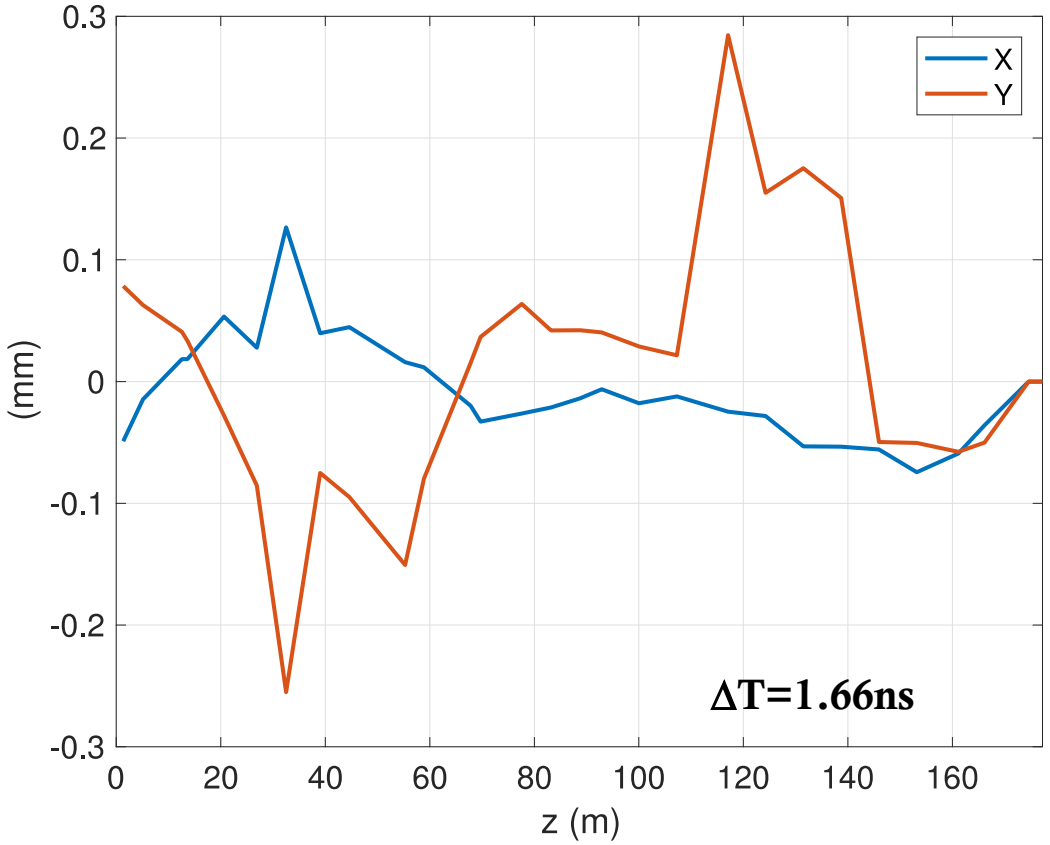




Conclusion: using the traj. feedback in two-bunch mode is not the best strategy, we need a new one.

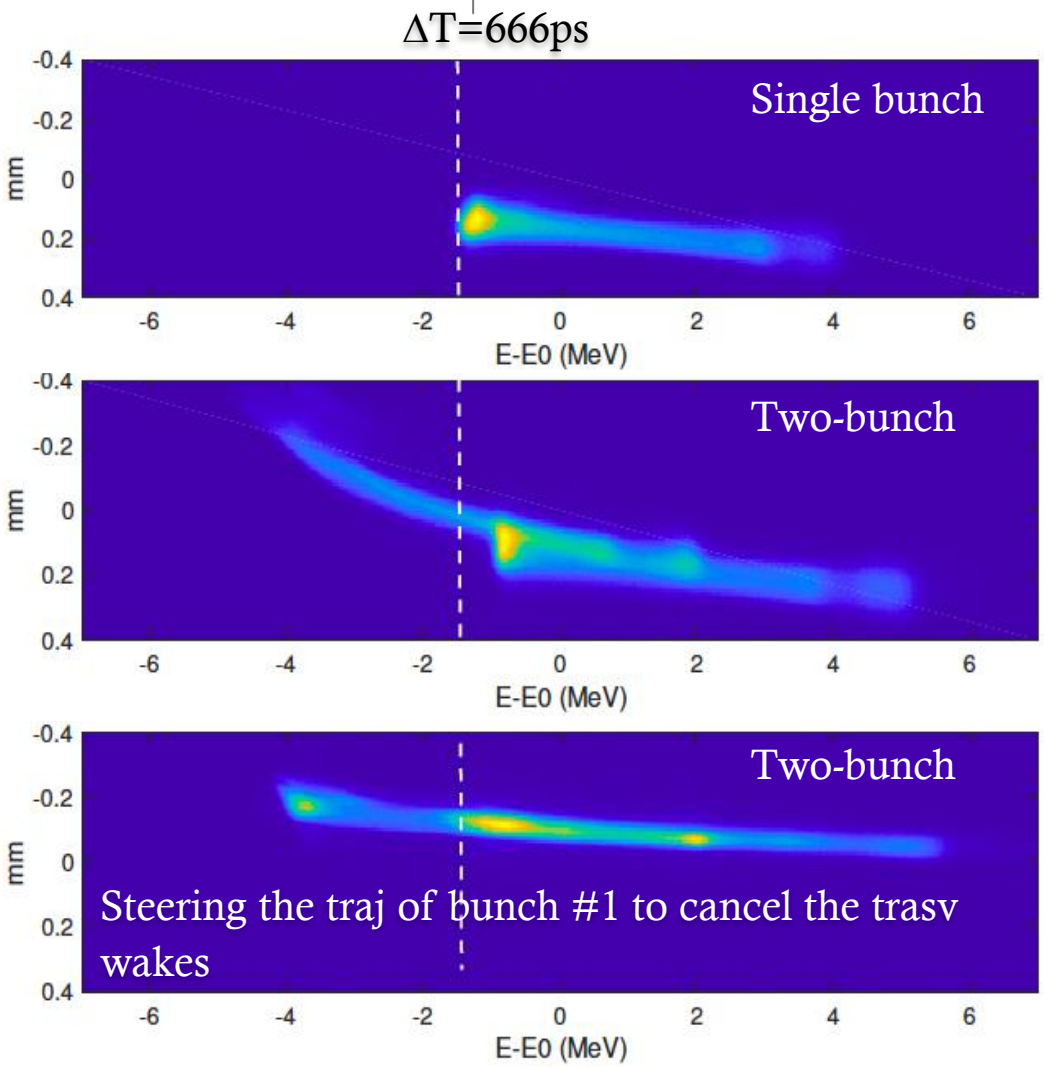
Two-bunch mode: from the gun to the MBD

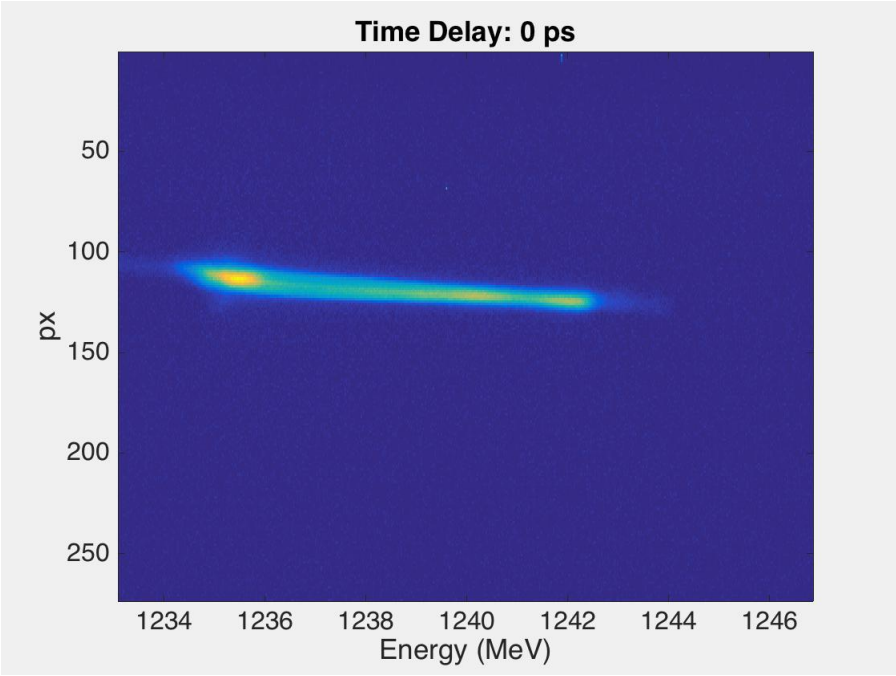
- The first bunch is used as reference (i.e. all feedback on with only bunch #1)
- All feedback in stand-by, close bunch #1, and open bunch #2
- Two bunches transported to the MBD: losses under control, trajectory of the "two-bunch system" as seen by BPMs within 300μm (rms)



- **Feedback disabled** otherwise it would steer off-axis each bunch symmetrically enhancing the trasv. wakes of the front bunch on the second one.
- **Diagnostic screens along the linac to check the transverse position** of both bunches, steering the 1st one to find the best compromise
- **Future upgrade** solution: dedicating a **small fraction of shots** to operate with only the drive bunch with the trajectory feedback enabled.

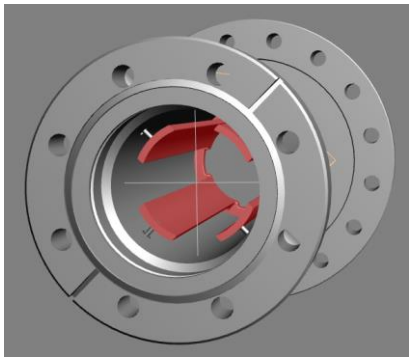
Two-bunch mode: energy spectrometer





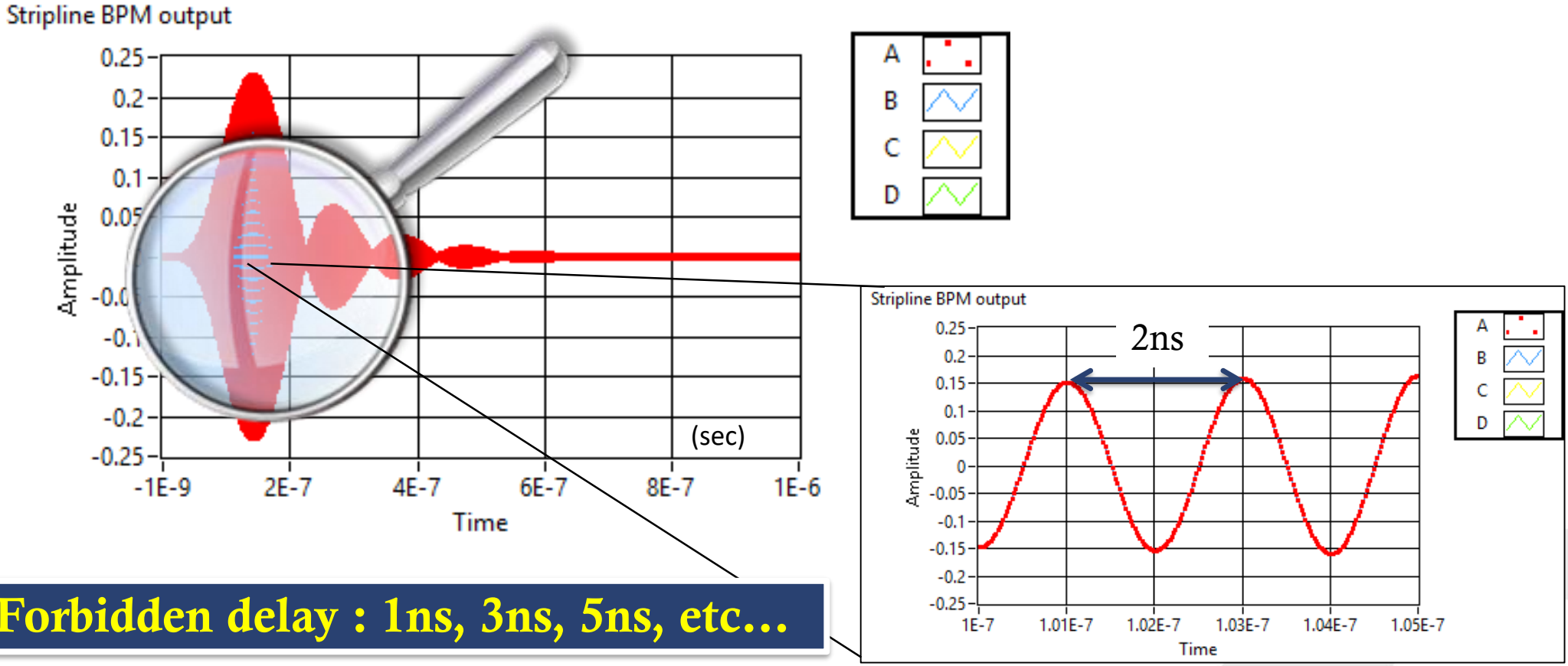
In two-bunch mode also the bunch #1 changes the energy due to the beam loading of the rf linac sections (hard to be compensated in few rf cycles)

BPM response simulation to two consecutive bunches



Considering that the signal generated by one bunch takes **1 ns** to reach the short-circuit on a BPM edge and be reflected back, a **2nd bunch with ΔT=1ns** perfectly cancels it.

Moreover, the BPM signal excites a sixth-order band-pass filter at 500 MHz, (bandwidth=10 MHz) with a resulting output oscillating pulse of about 1 μs.



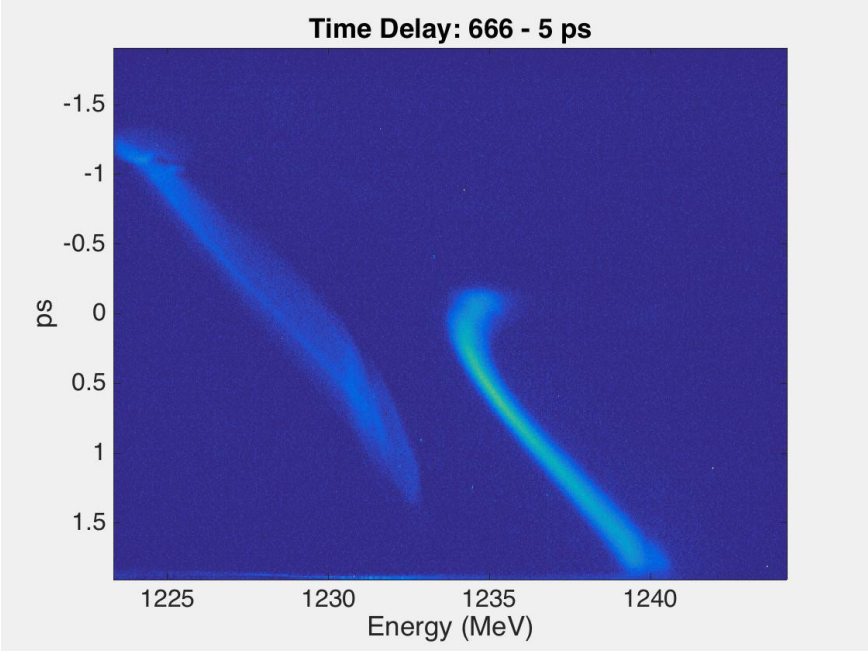
Forbidden delay : 1ns, 3ns, 5ns, etc…

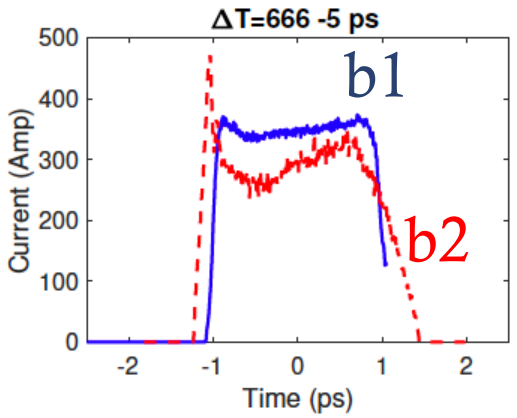
Manipulation of the Long Phase Space: tuning ΔT

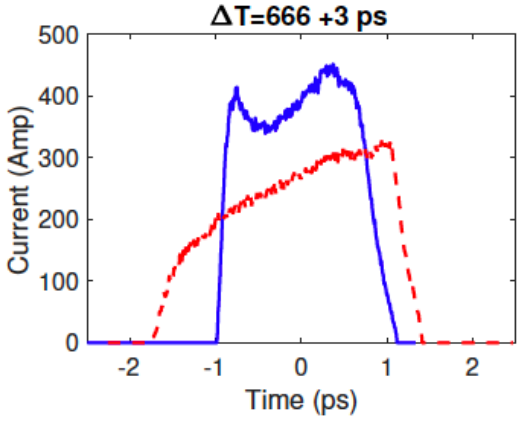
Vertical RF Deflector + Energy Spectrometer (DBD) -> Long Phase Space Measurement

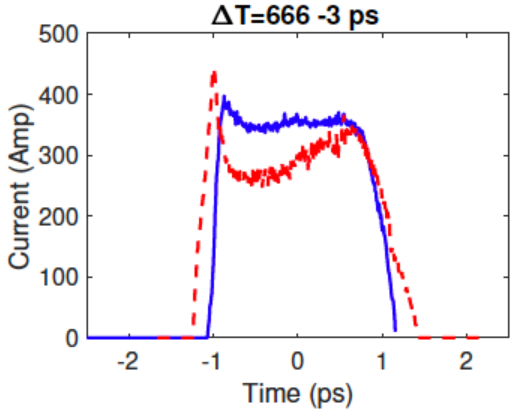
Changing the time-delay by few ps:

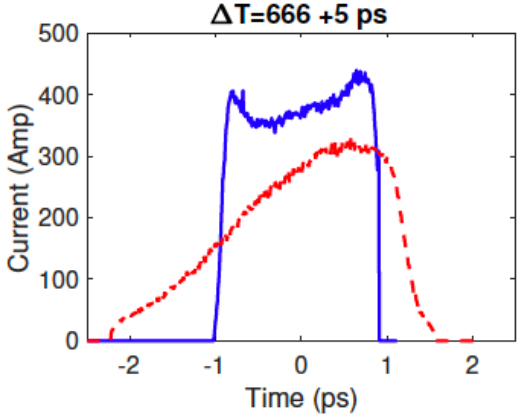
- The bunch #2 sampled a slightly different RF gun phase (~ from -5 to +5 deg):
- Different charge (Schottky effect)
- Shifting of the linac phase with a consequently different compression factor





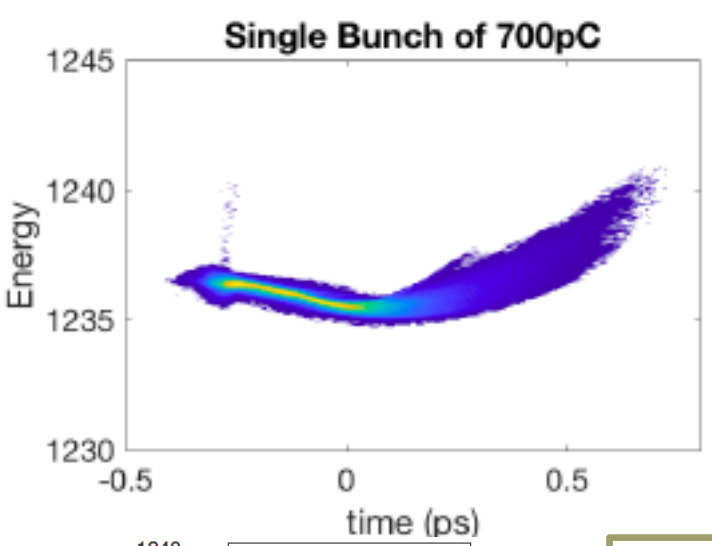


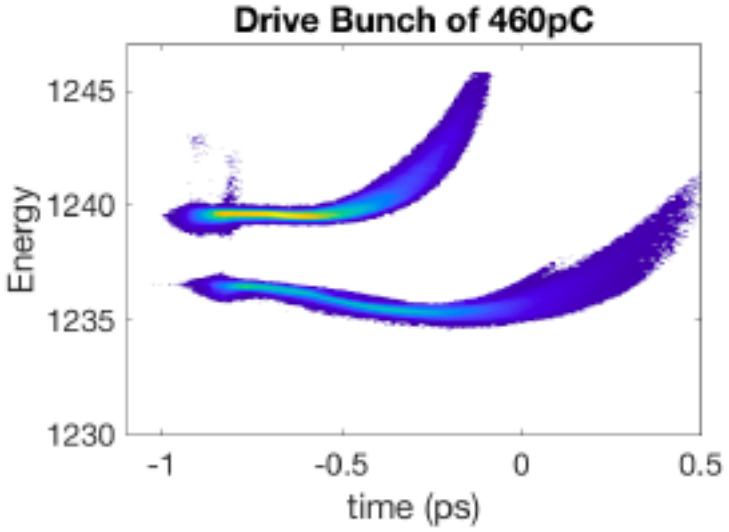


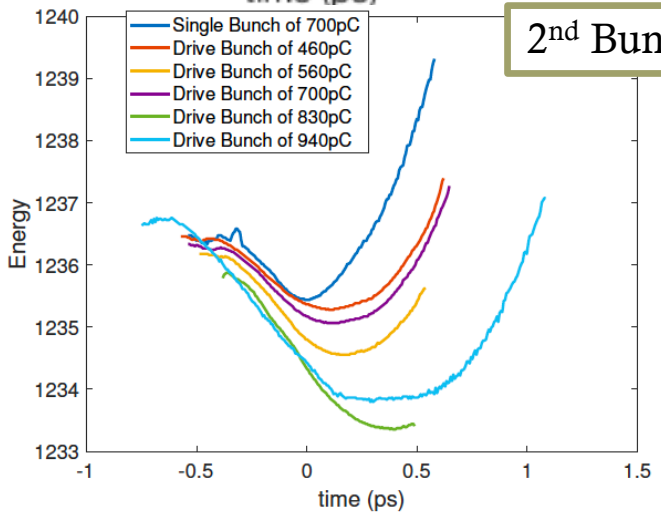


Manipulation of the Long Phase Space: tuning Charge

Fixed temporal separation of 0.66ns. Changing Q1 changes the long. wakes acting on the trailer bunch, but changes also the wakefields acting on the drive bunch itself: **energy (i.e. compression)** and **arrival time (compression and relative delay with the trailer bunch)**





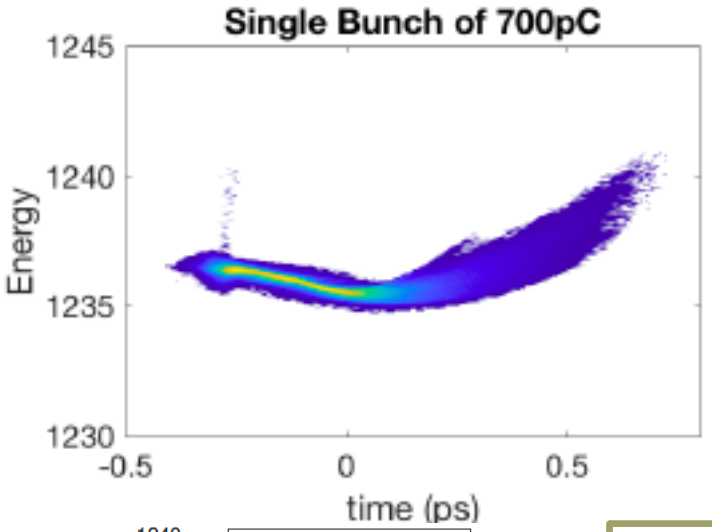


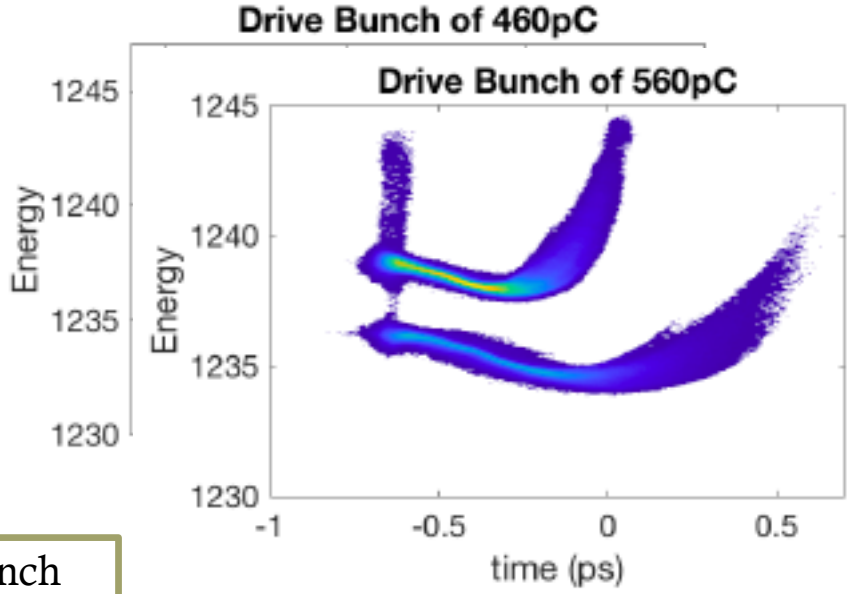
2nd Bunch

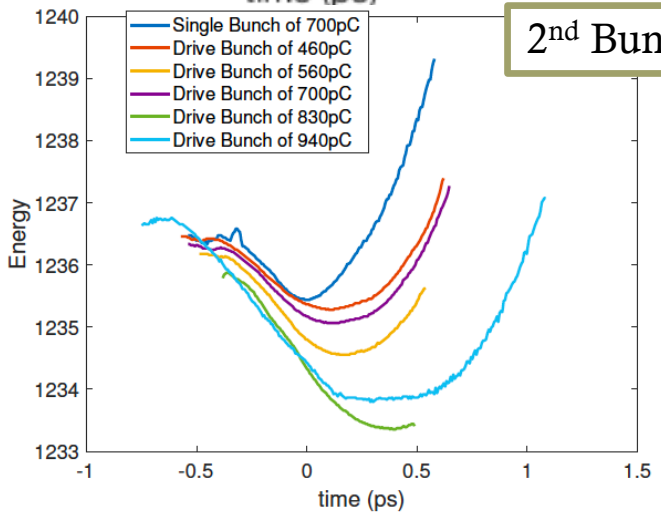
Tuning the **Drive Bunch Charge** allows to manipulate the longitudinal phase space of **Both Bunches**.

Manipulation of the Long Phase Space: tuning Charge

Fixed temporal separation of 0.66ns. Changing Q1 changes the long. wakes acting on the trailer bunch, but changes also the wakefields acting on the drive bunch itself: **energy (i.e. compression)** and **arrival time (compression and relative delay with the trailer bunch)**







2nd Bunch

Tuning the **Drive Bunch Charge** allows to manipulate the longitudinal phase space of **Both Bunches**.

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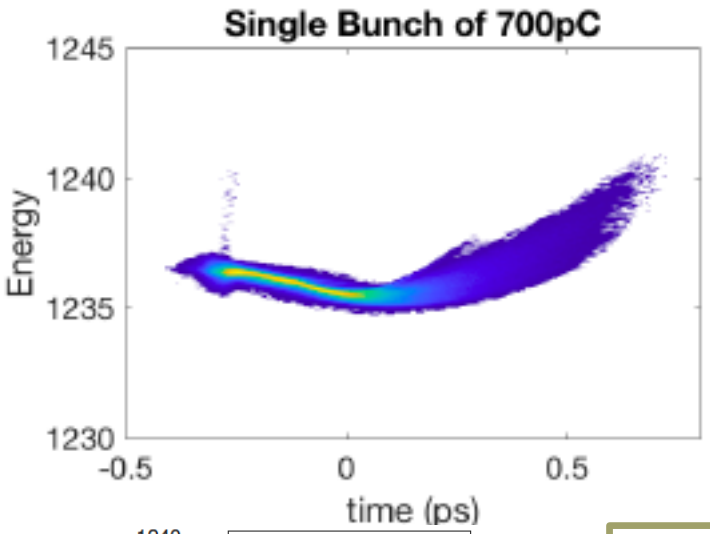

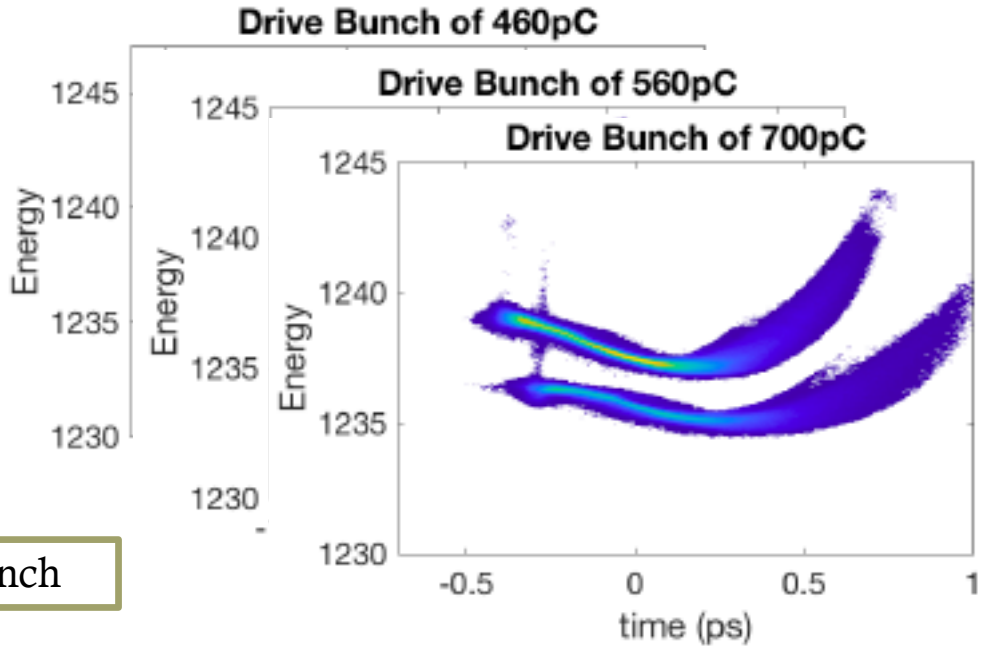

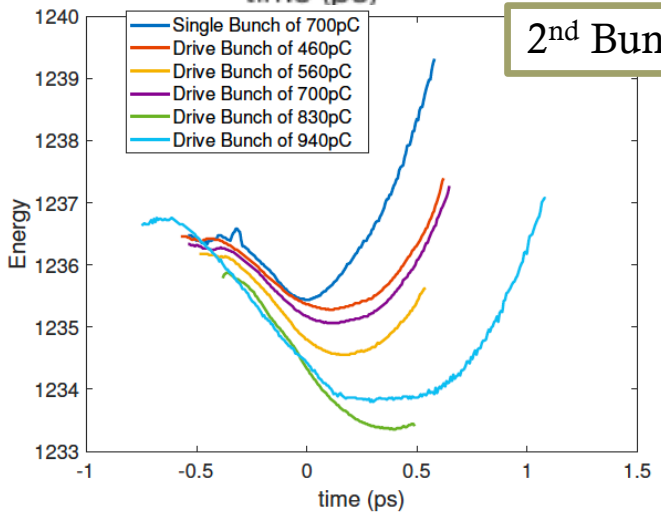

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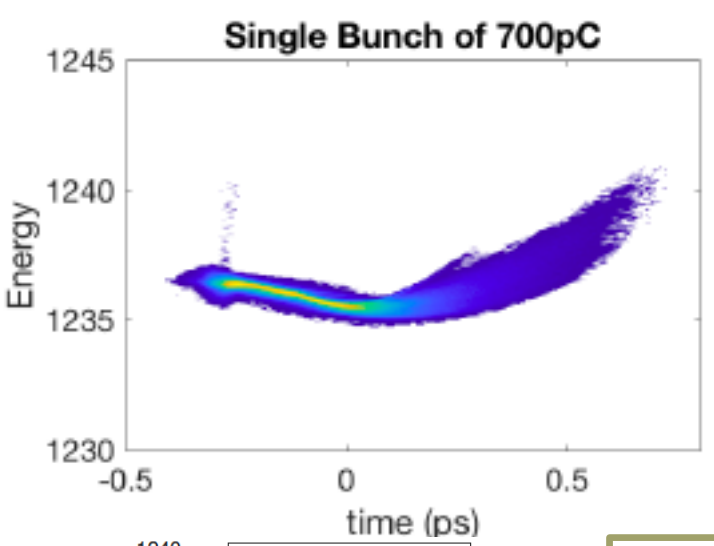

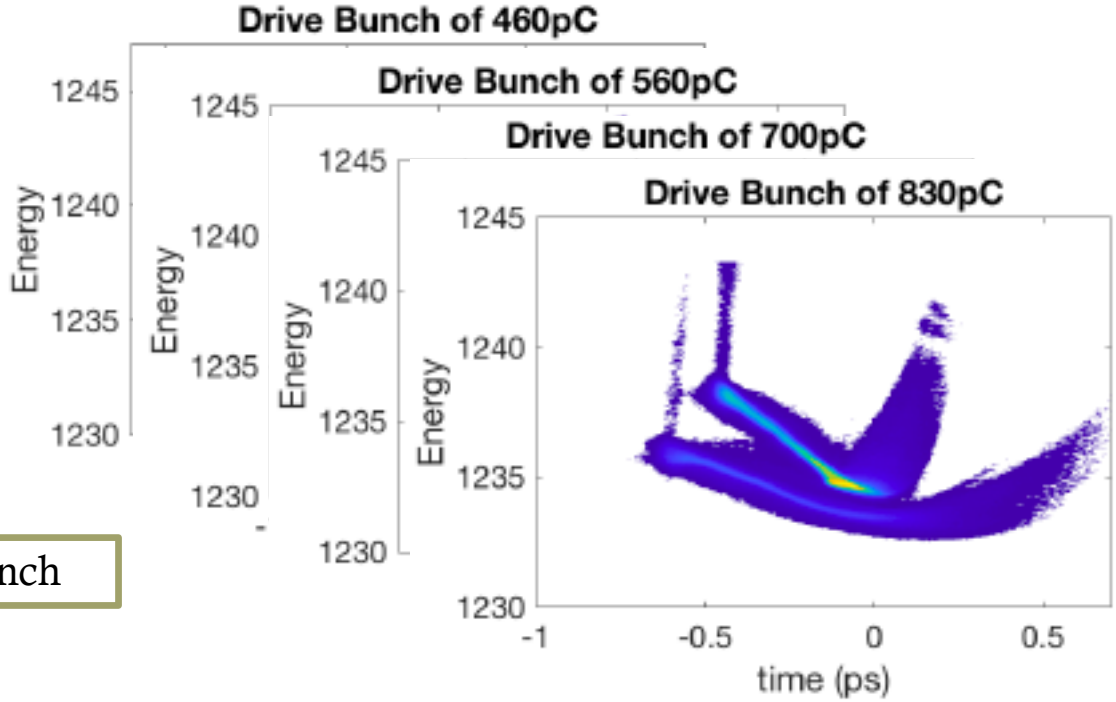

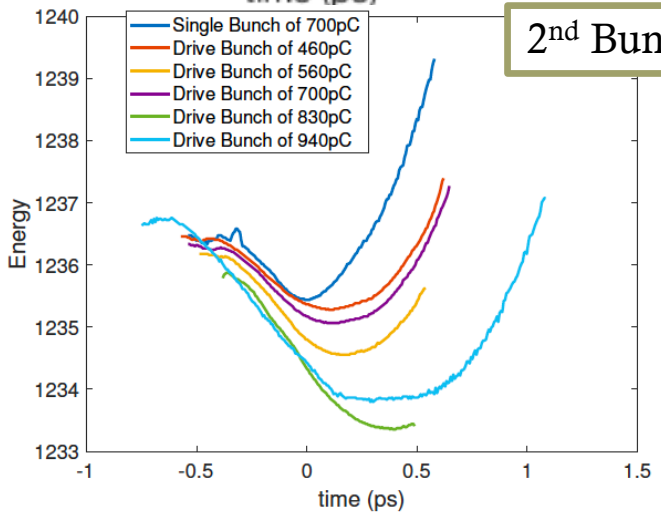

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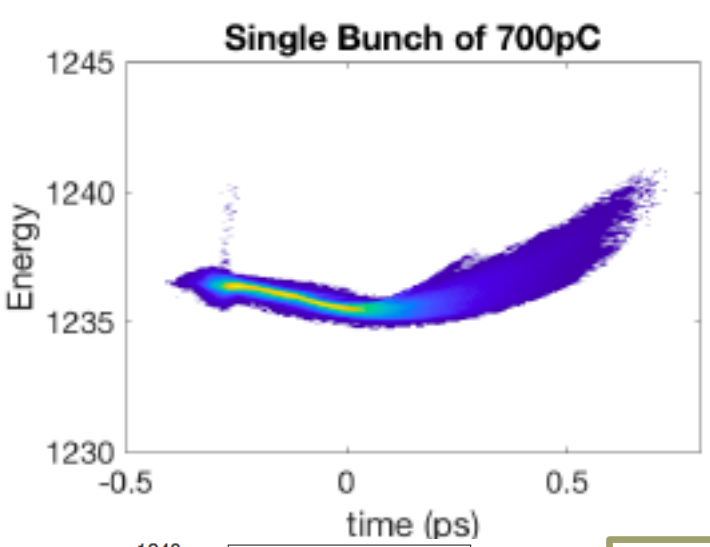

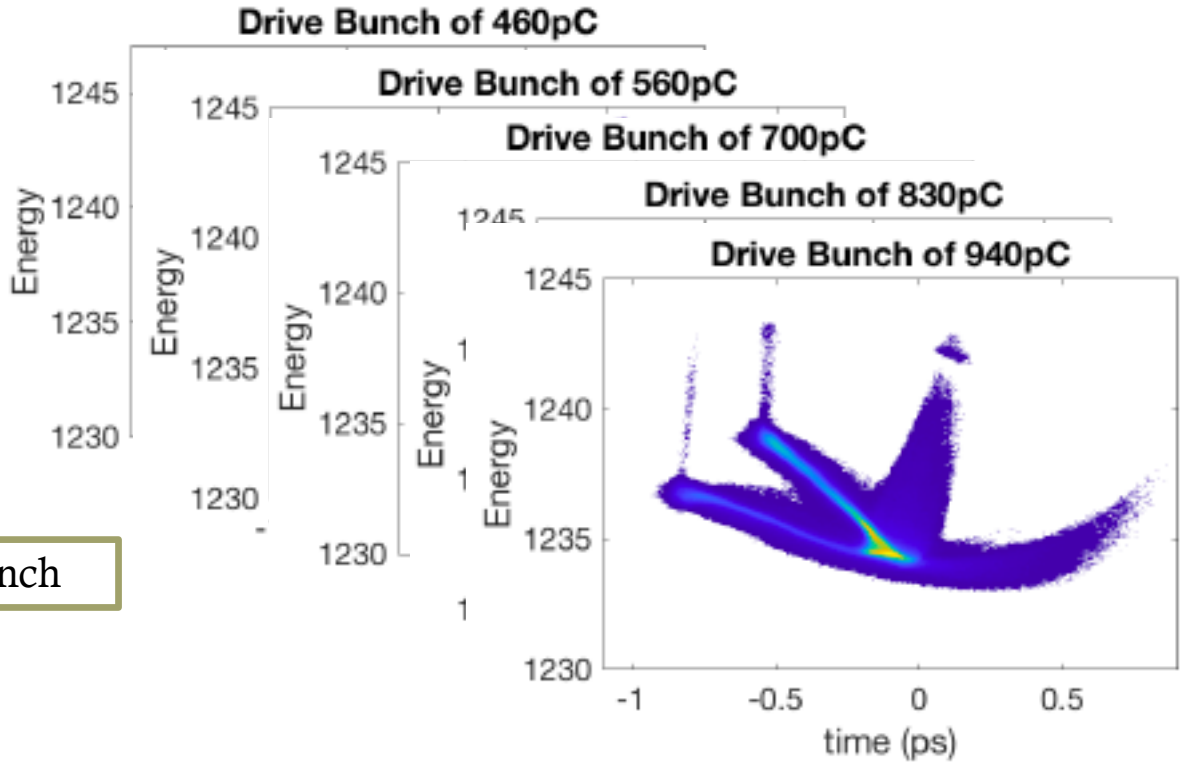

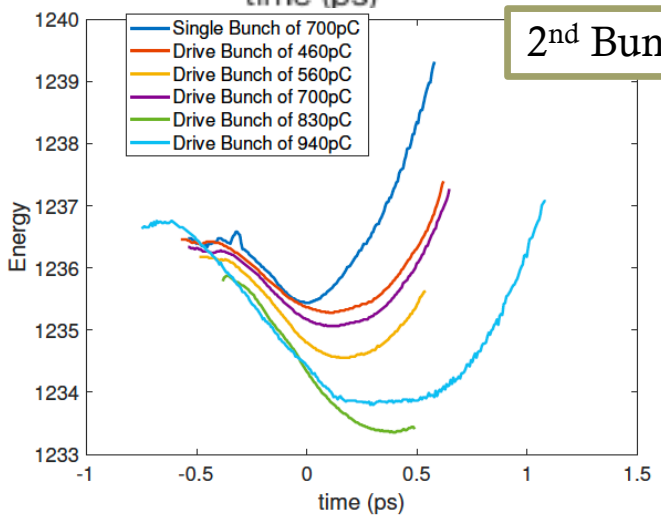

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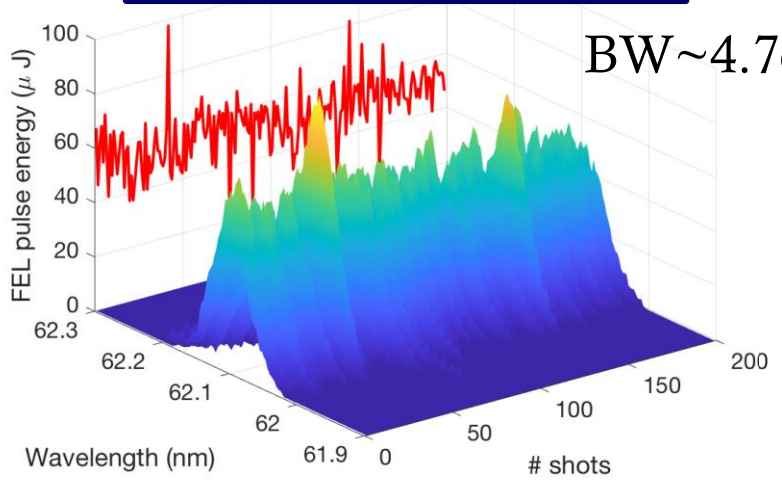
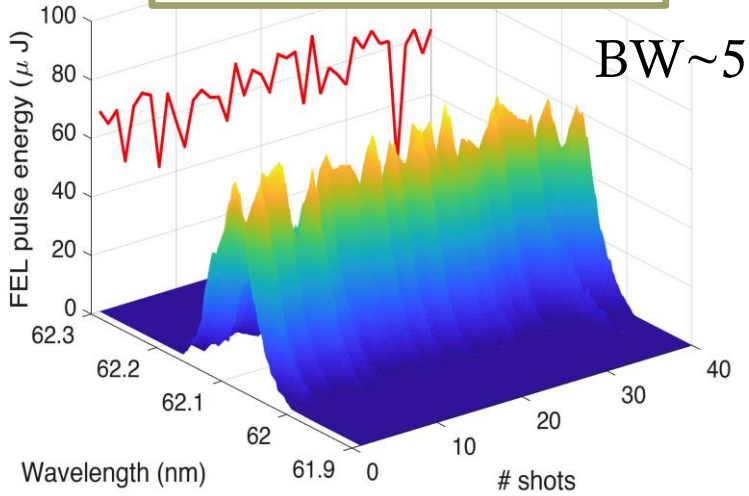
FEL in two-bunch mode: proof of principle

Seeding the drive bunch
(Q1=700pC, Q2=700pC)



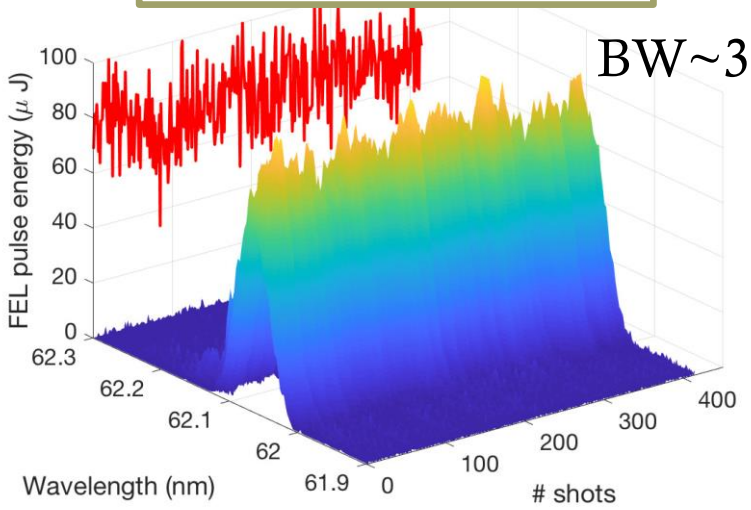
BW~4.7e-4

Seeding the trailer bunch
(Q1=700pC-Q2=700pC)



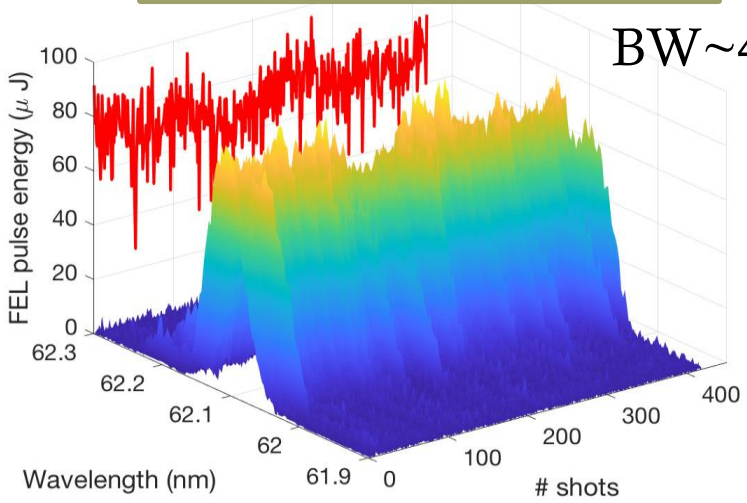
BW~5.0e-4

Seeding the trailer bunch
(Q1=550pC-Q2=700pC)



BW~3.8e-4

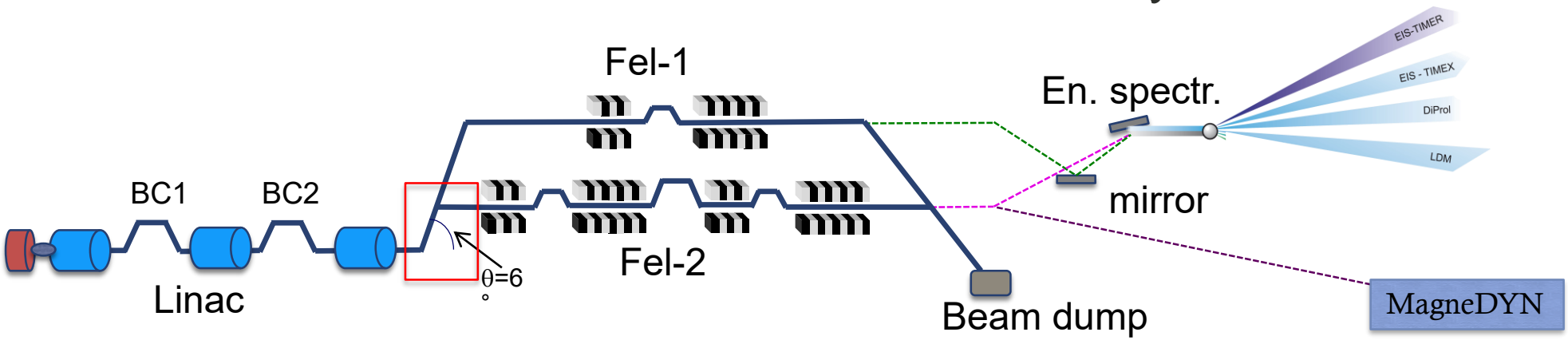
Seeding the trailer bunch
(Q1=480pC-Q2=700pC)



BW~4.2e-4

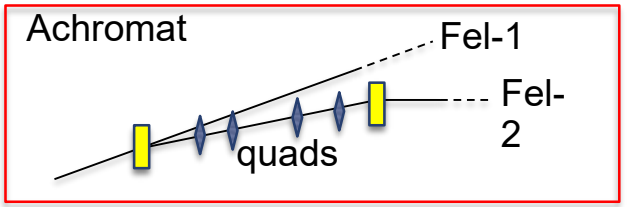
Possible Future Upgrade:

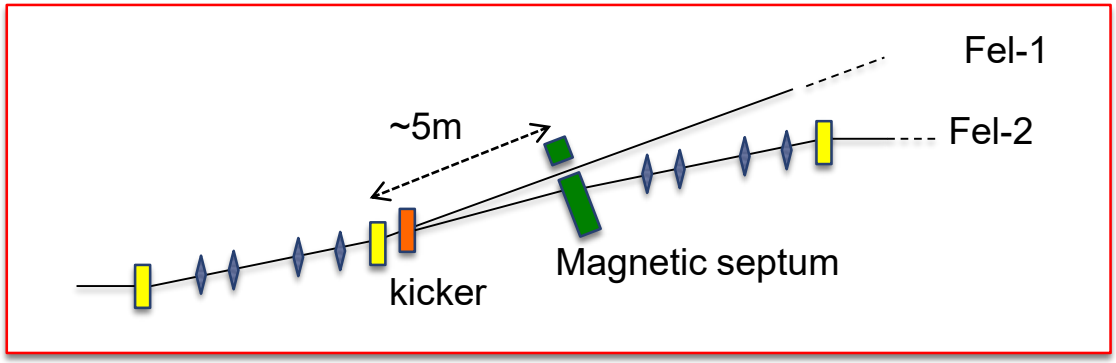
FEL-1 and FEL-2 simultaneously



The layout naturally suggests this option that however requires important modifications:

- New design of the Spreader Common Line





KICKER OPTION

- **Fast high Q-factor resonant deflecting magnet** by SwissFEL (M. Paralier et al. Proc. FEL 2014): **ΔT=28ns**, demonstrated a shot-to-shot amplitude stability of ±9-11 ppm, time jitter of 25ps (ptp)
- Sub-harmonic RF-deflector phased to kick them at +π/2 and –π/2 (limiting the transverse momentum) and the best solution would be a 1.5-GHz rf-deflector (largest flexibility)

ULTIMATE CHALLENGE:
Consider the possibility to recombine Fel-1 and Fel-2 output for pump-probe experiment

Conclusion

- Two-bunch operation at FERMI has been successfully tested: transport through FEL-1 undulator line up to the MBD
- Studies of the Long-range wakefields induced by the drive bunch affecting the traj and energy of the trailing bunch: fine tuning the charge and/or the time-delay allows to manipulate the long phase space
- Lasing on FEL-1 in two-bunch mode with good performance, close to the nominal one.
- Forthcoming application: THz-pump FEL-probe experiment by using the trailer bunch for the FEL emission and the 1st bunch for producing synchronized THz light in the TeraFERMI line
- Future advance option: operation of FEL-1 and FEL-2 simultaneously and/or recombining the ouput radiations for pump-probe experiments

Elettra
Sincrotrone
Trieste

Acknowledgement:

- FERMI control team, radio-protection team, commissioning and operation team for the valuable support during the machine setting and optimization
- PADReS team for taking care of the photon transport and spectrometer setup during the FEL measurements.

Thank you

谢谢

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