

MAX IV linac operation

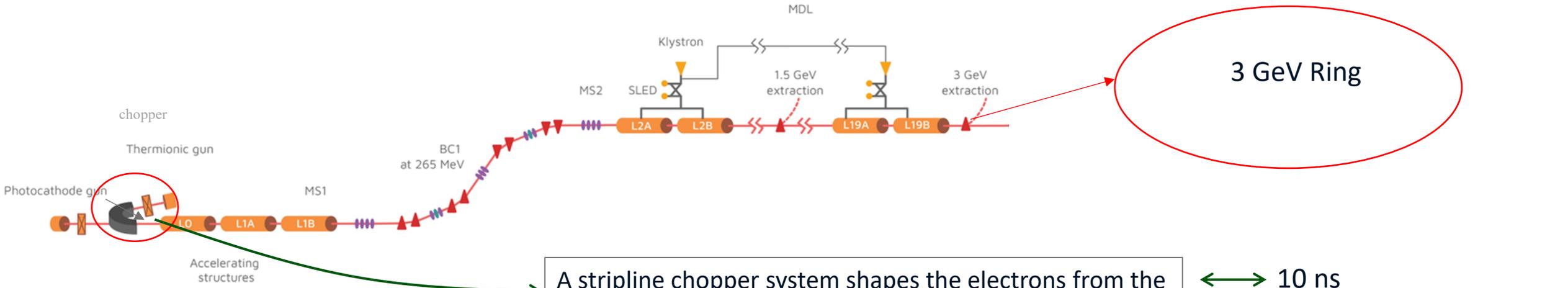
Workshop on full energy injection

Sara Thorin

Outline

- Injection with a thermionic RF gun
- Injection modes in the storage rings
- New injection capabilities: photo cathode gun
- Day to day operation
- Off phase, on axis injection for MAX4^U

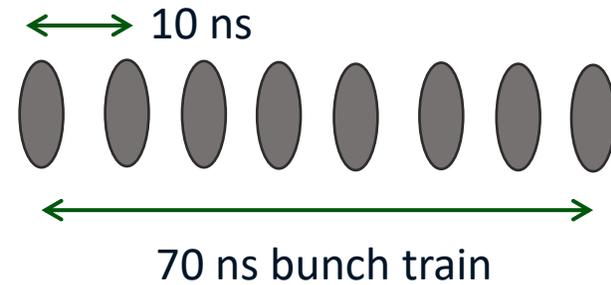
Linac as injector: thermionic gun



Full energy injection and top up operation for the two storage rings

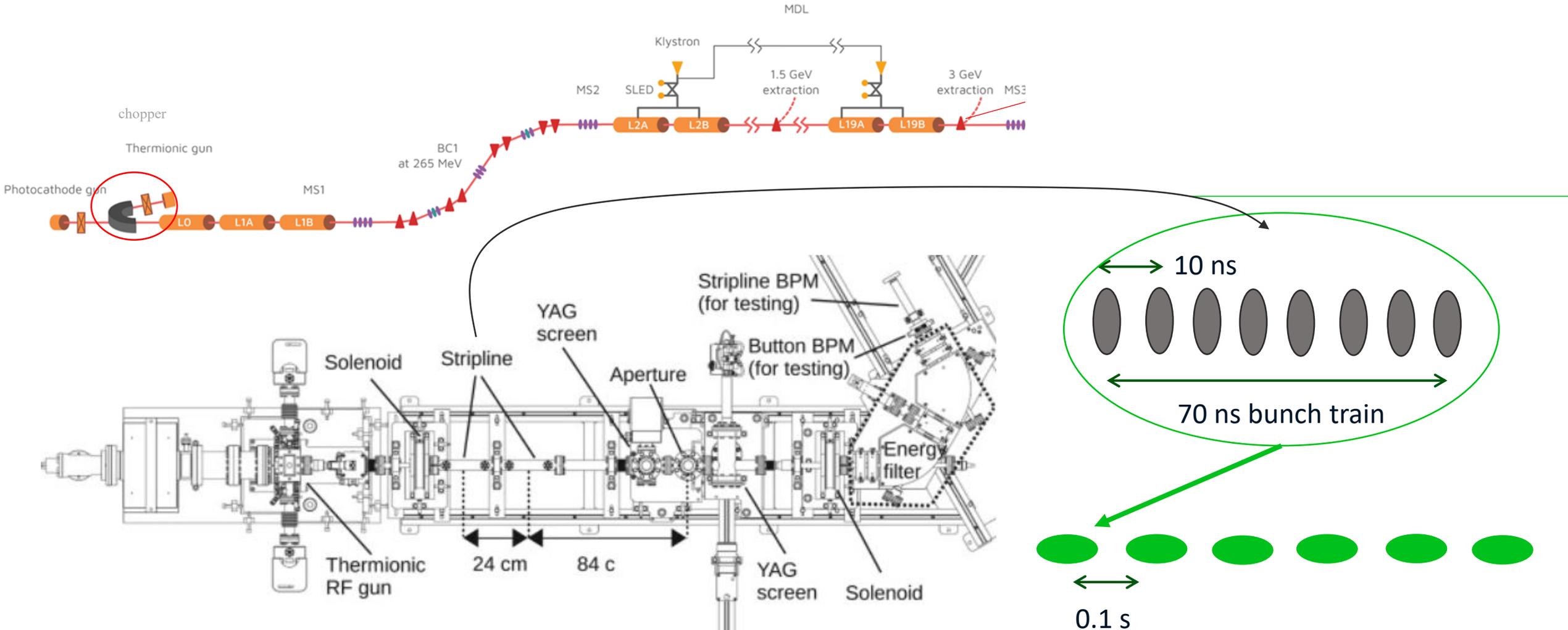
Energy	1.5 GeV/ 3GeV
Repetition rate	10 Hz
Charge	300 pC/shot
Emittance	5 mm mrad
Energy spread	<0.3 %

A stripline chopper system shapes the electrons from the thermionic gun in 10-100 ns macro bunches with a separation of 10 ns to match the 100 MHz ring RF frequency.



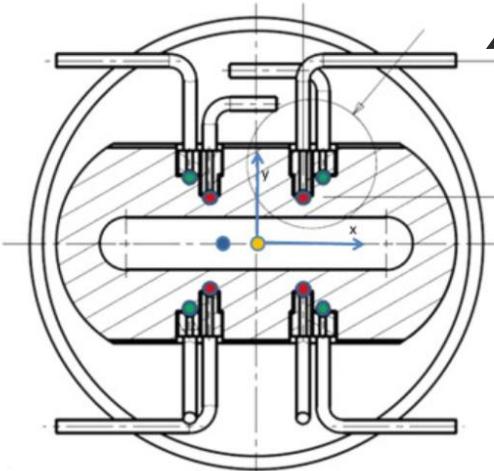
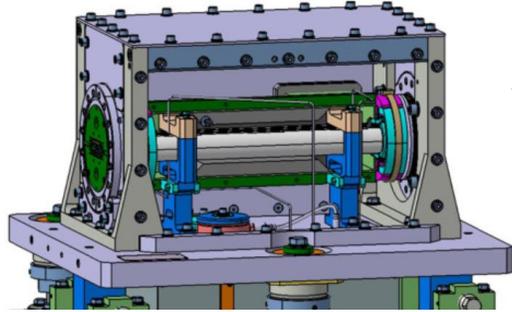
- High Charge per pulse
- ~8 buckets filled at every shot
- ~ 3 S-band bunches per ring bucket.
- Requires large phase acceptance in the ring
- Larger energy spread over the bunch train
- Allows off-axis, on-energy injection scheme, with high injection rate

Linac as injector: thermionic gun

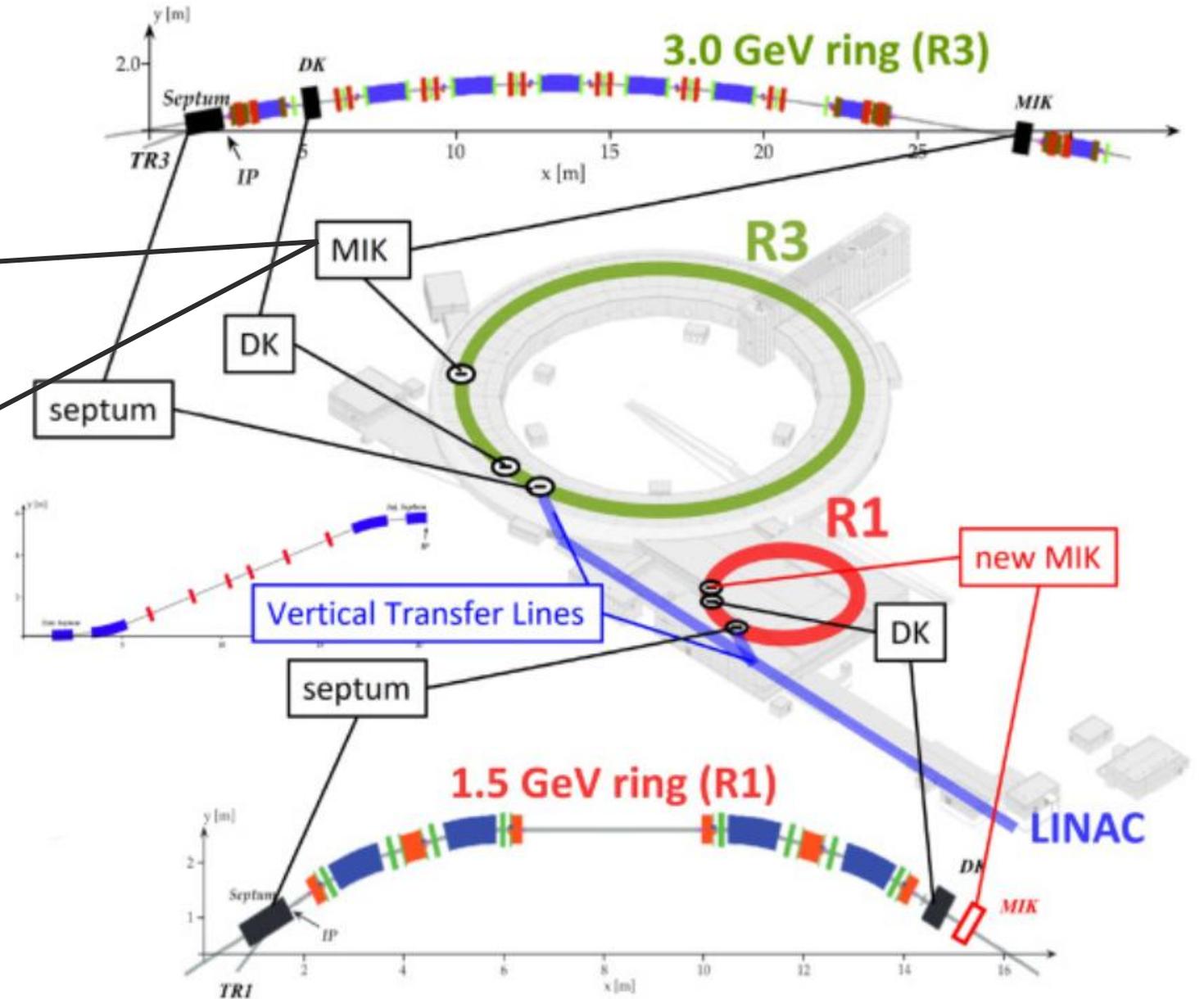


D. Olsson et al., *MAX IV thermionic pre-injector chopper system*, NIM A, 2014

Injection



P. Alexandre, *et al.*
Transparent top-up injection into a fourth-generation storage ring
Nucl. Inst. Methods Phys. Res. A, 986 (2021)



M. Apollonio et al., *Commissioning of the Multipole Injection Kicker in the MAX IV 1.5 GeV ring*, NIM A, 2025.

Linac as injector: photogun

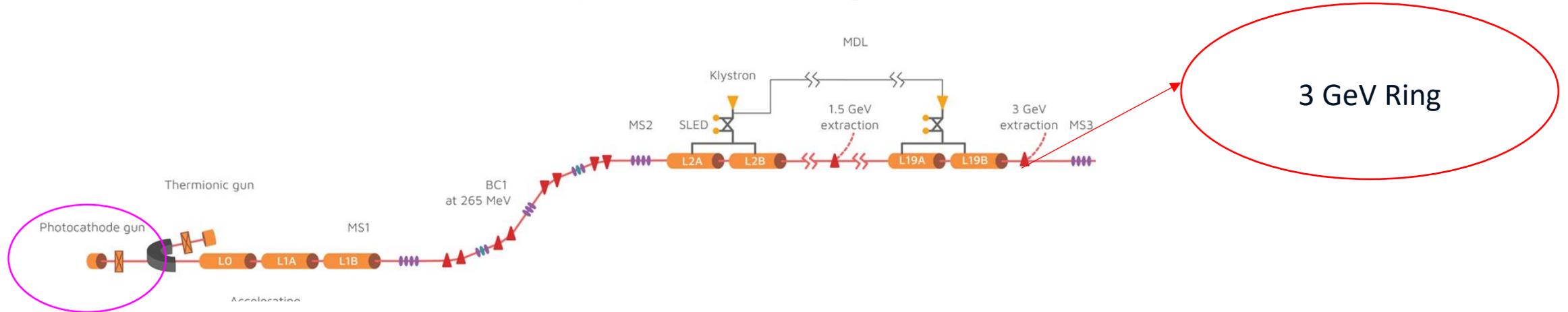


Photo cathode gun for ring injection

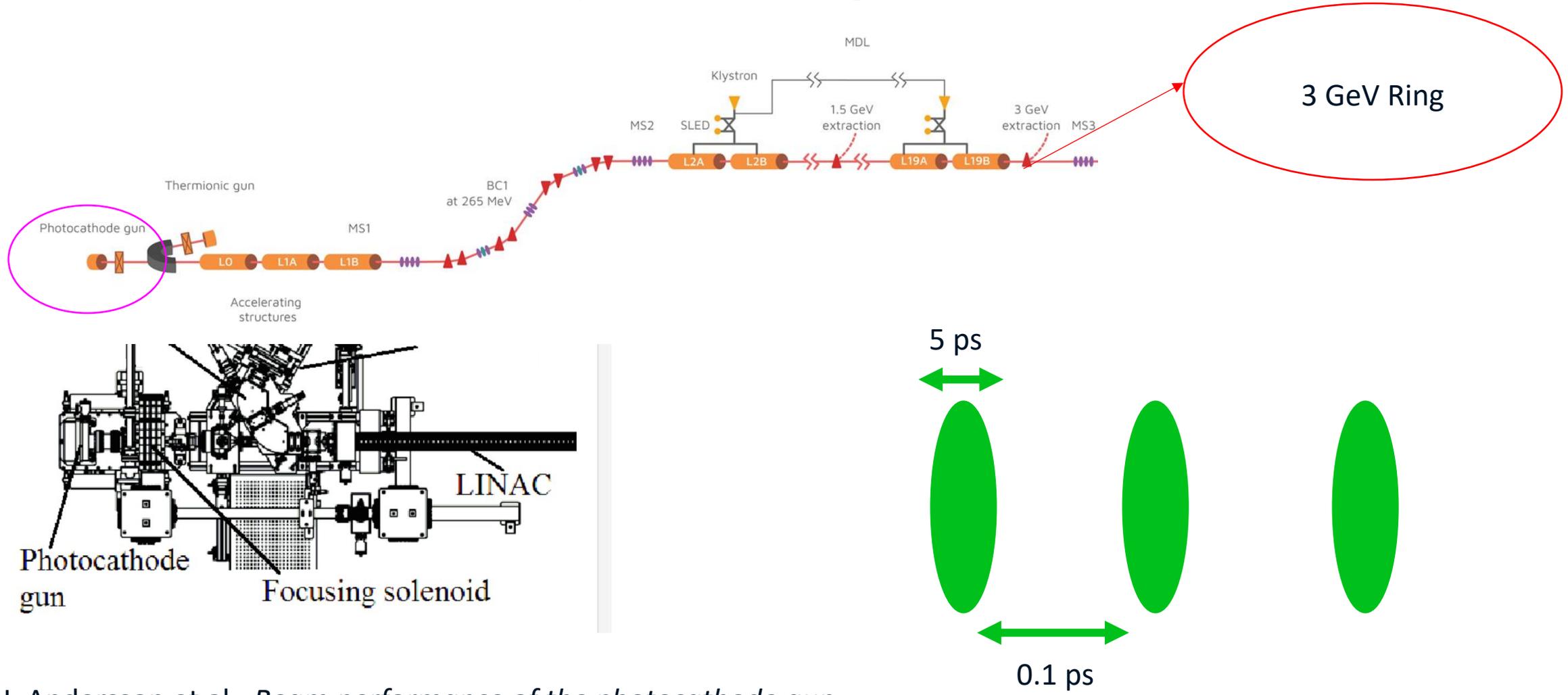
Energy	3 GeV
Repetition rate	10 Hz
Charge	200 pC
Bunch length (rms)	~5 ps
Emittance	2-3 mm mrad
Energy spread (rms)	<0.05%

- lower charge per pulse
- 1 bucket filled at every shot
- 1 S-band bunch per ring bucket.
- Small phase extension, small bunch length and energy spread

Current Injection parameters

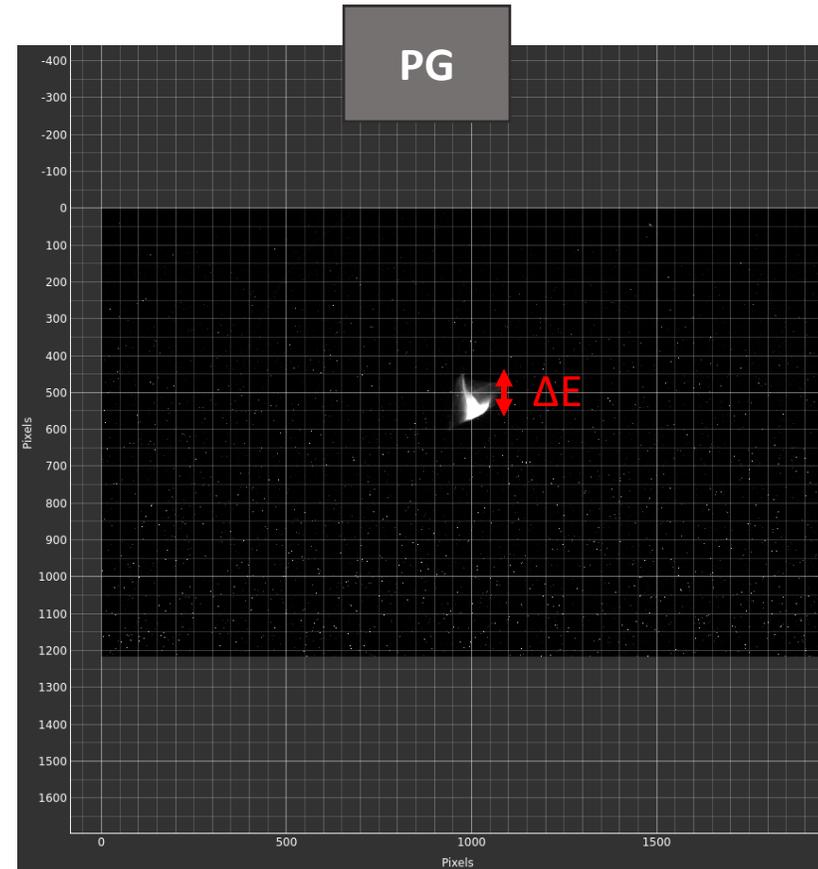
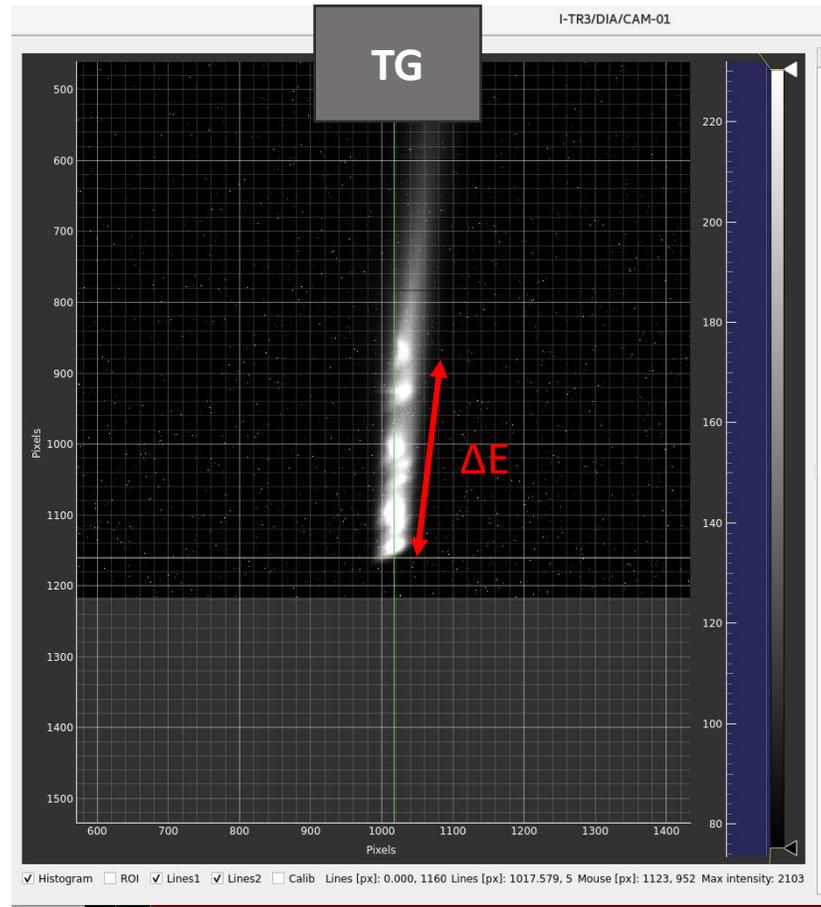
- Pulse duration ≈ 5 ps (0.18°)
- Phase jitter ≈ 150 ps rms (4°)
- Energy spread $< 5 \cdot 10^{-4}$
- Energy jitter $< 5 \cdot 10^{-4}$
- Charge ≤ 150 pC

Linac as injector: photogun



J. Andersson et al., *Beam performance of the photocathode gun for the MAX IV LINAC*, FEL 2014.

Beam difference On screen1 in TR3



Coincidence system for injection timing

- linac rf frequency is not a multiple of the ring frequency.
- This is not an issue when using the thermionic gun given the long macropulse and the use of a chopper that imparts the ring time-structure onto the LINAC S-band pulse train
- A coincidence detector gives a trig when a ring bucket and a possible shot from the photo cathode gun overlap in time. The linac is then triggered to produce an injection shot.
- Rep rate 2-10 Hz (require coincidence system intervention to change)

Choose which ring bucket to inject into

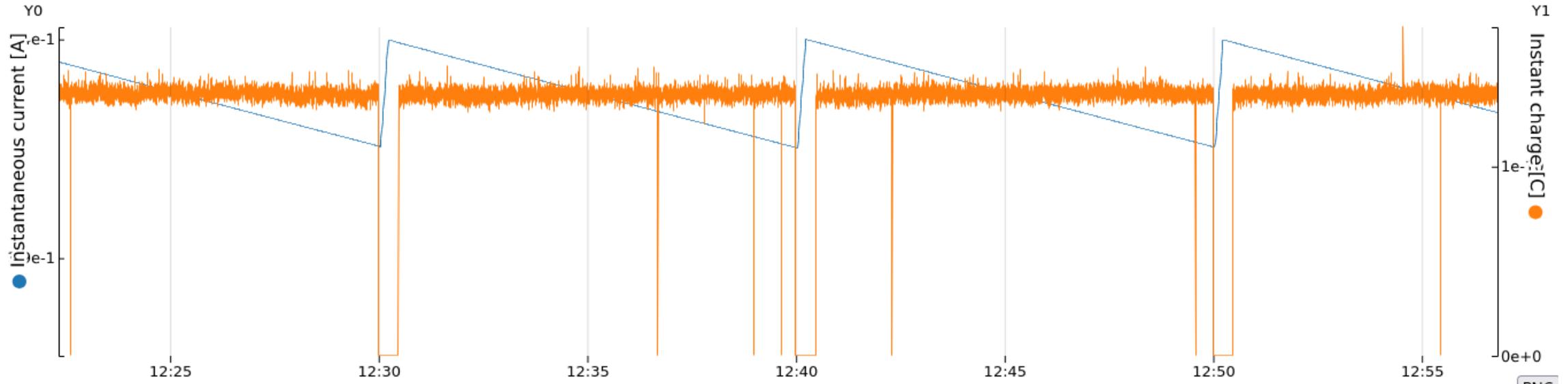
Choose time window for coincidence.
- This sets the phase precision jitter. Smaller window means less phase jitter, but also fewer coincidences.

Delay of the injection shot.
- This sets where in the ring phase the injection occurs. Precision of 40 ps (1.5°)

The screenshot shows a control interface for a coincidence system. It features a list of parameters on the left, each with a corresponding control field on the right. The 'Delay fine offset' parameter is highlighted with a pink oval, and three pink arrows point from text boxes to the 'Inject bucket', 'Time window', and 'Delay fine offset' parameters.

Inject bucket	0 nbr	▲▲▲ 0	...
Time window	499.0 ps	▲▲▲▲▲ 499.0	...
Delay fine offset	108 taps	▲▲▲ 108	...
Delay 2.5 ns steps	4 2.5 ns steps	▲▲▲ 4	...
Laser trigger source	COINCIDENCE	Not initialised	...
Ring RF source	REV_CLOCK	REV	...
Linac trig outdelay	0.00040565 s	▲ . 00040565	...
Diagnostics trig outdelay	0.00000000 s	▲ . 00000000	...
Laser trig outdelay	0.01549405 s	▲ . 01549406	...
Laser 100 Hz trig outdelay	0.00049304 s	▲ . 00049304	...
Laser 500 Hz trig outdelay	0.00000000 s	▲ . 00000000	...

Day to day operation



- Top up in R3 and R1 every 10 minutes
- SPF delivery at all other times
- Switching time a few seconds, top up time a few seconds – total ~30s
- Controlled by the State Machine (more info in Filip's talk)

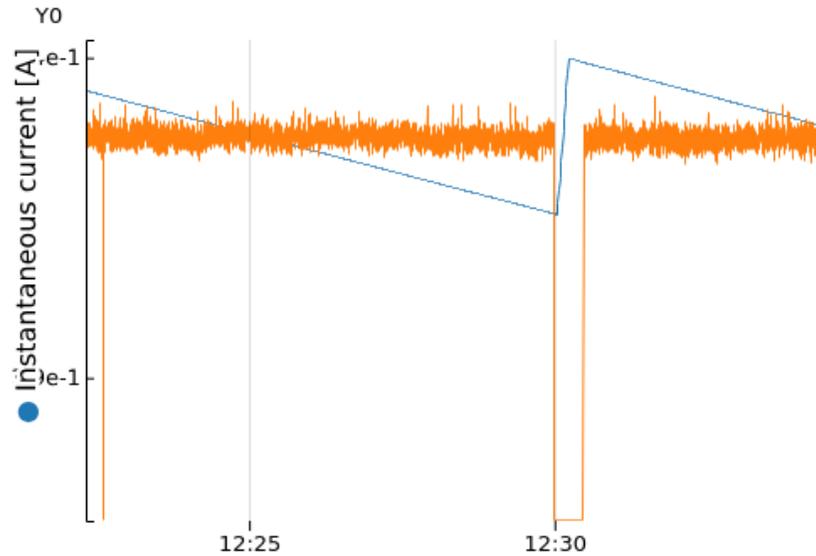
R3 number of buckets	<input type="text" value="176"/>	<input type="text" value="0"/>
R3 step length	<input type="text" value="7"/>	<input type="text" value="0"/>
R3 scheduled injection interval	<input type="text" value="10 min"/>	<input type="text" value="0 min"/> min
R3 use PG Injection	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
R3 use single bunch	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
R3 use reduced charge	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
R3 use MIK	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
R3 use fillpattern feedback	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
R3 use bucket weights	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
R3 use injection feedback	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>

InjectR3

Toggle R3 state	<input checked="" type="checkbox"/>	<input type="checkbox"/>
R3 max current	<input type="text" value="3.00 mA"/>	<input type="text" value="3"/> mA
R3 min current	<input type="text" value="399.00 mA"/>	<input type="text" value="0.00 mA"/> mA
R3 snapshot	<input type="text" value="11328"/>	<input type="text" value="11328"/>
R3 use snapshot	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
R3 temporary snapshot	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
R3 use trimming mode	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
R3 latest injection rate	<input type="text" value="43.8"/>	<input type="text" value=""/> mA / min
R3 latest injection efficiency	<input type="text" value="51"/>	<input type="text" value=""/> %
Injection Frequency Running	<input type="text" value="10.0"/>	<input type="text" value=""/> Hz

StopInjectR3

Day to day operation



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- SPF delivery at all other times
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2025 Accelerator Operations Statistics

Accelerator	Planned delivery [hours]	Uptime	MTR [hours]	MTBF [days]
3 GeV Ring	4968	97.0% 😊	2.7	3.8
1.5 GeV Ring	4968	99.1% 😊	1.6	8.0
SPF	4536	97.4% 😊	0.77	0.4

R3 use single bunch

R3 use reduced charge

R3 use MIK

R3 use fillpattern feedback

R3 use bucket weights

R3 use injection feedback

R3 use snapshot

R3 temporary snapshot

R3 use trimming mode

R3 latest injection rate 43.8 mA / min

R3 latest injection efficiency 51 %

Injection Frequency Running 10.0 Hz

InjectR3
StopInjectR3

Off-phase, on-axis injection Scheme MAX4^U



Current Injection parameters

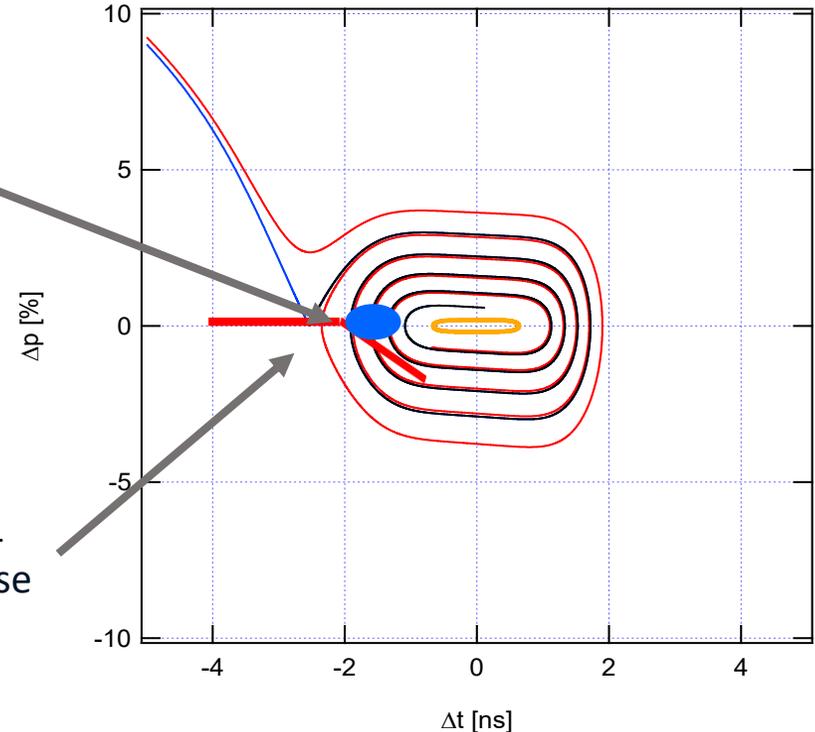
- Pulse duration ≈ 5 ps (0.18°)
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- Energy spread $< 5 \cdot 10^{-4}$
- Energy jitter $< 5 \cdot 10^{-4}$
- Charge ≤ 150 pC

- Our injector (full-energy linac) and low (100 MHz) ring RF frequency puts us in a privileged position to implement these schemes

- This approach
 - Allows advanced IDs with small horizontal gap.
 - Improves top-up transparency.
 - Eases accumulation into lattices with small dynamic aperture.

Photo gun electrons from the linac

Ultra fast stripline kicker –falltime ~ 1 ns, total kicker pulse ~ 2.5 ns



- Electron bunch injected on-axis, off phase in the ring RF bucket
- Fast kicker with minimal interference to the stored bunch

Summary

- MAX IV uses a full-energy LINAC injector for storage ring injection.
- Thermionic gun injection enables high charge and efficient multi-bucket filling using a chopper system.
- Photocathode gun injection provides lower charge per pulse but better beam quality and timing control.
- A coincidence timing system synchronizes LINAC shots with storage ring buckets.
- Routine operation includes top-up injection in R1 and R3 every ~10 minutes with fast switching to deliver to the SPF.
- Off phase, on axis injection considered for MAX4^U