Start-to-end simulations for an X-ray FEL Oscillator at the LCLS-II and LCLS-II-HE

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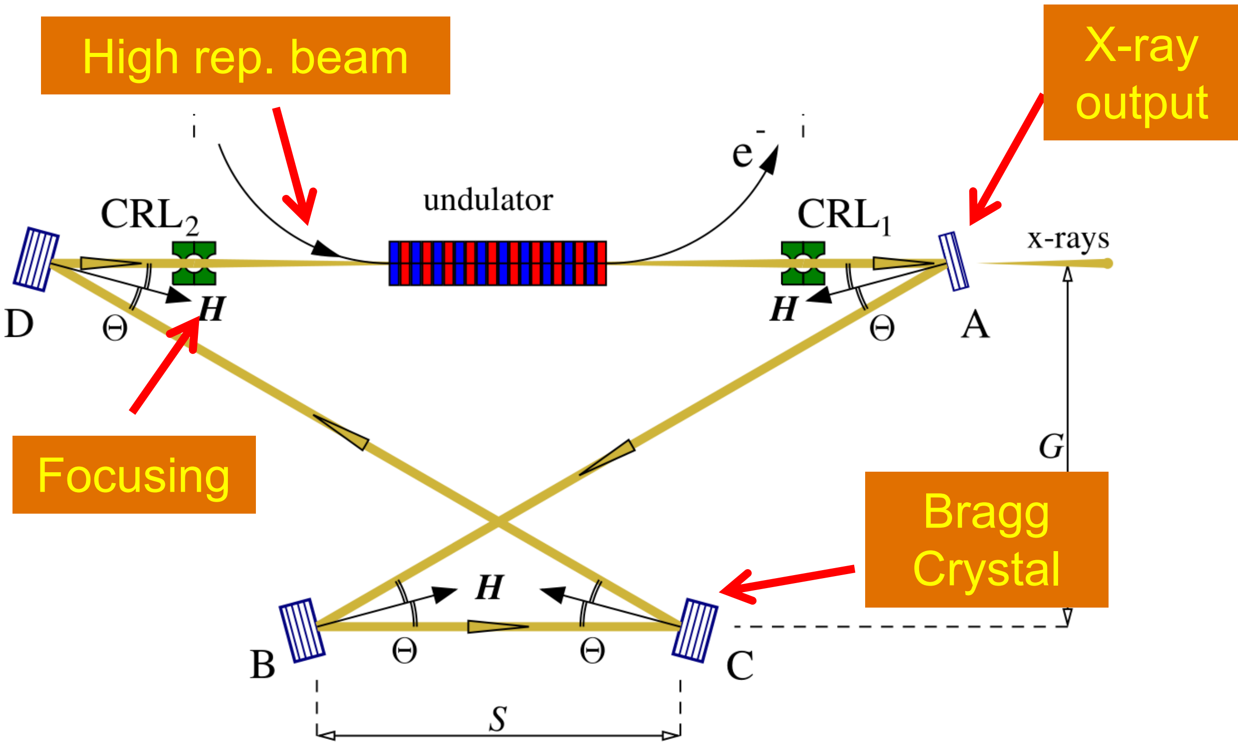
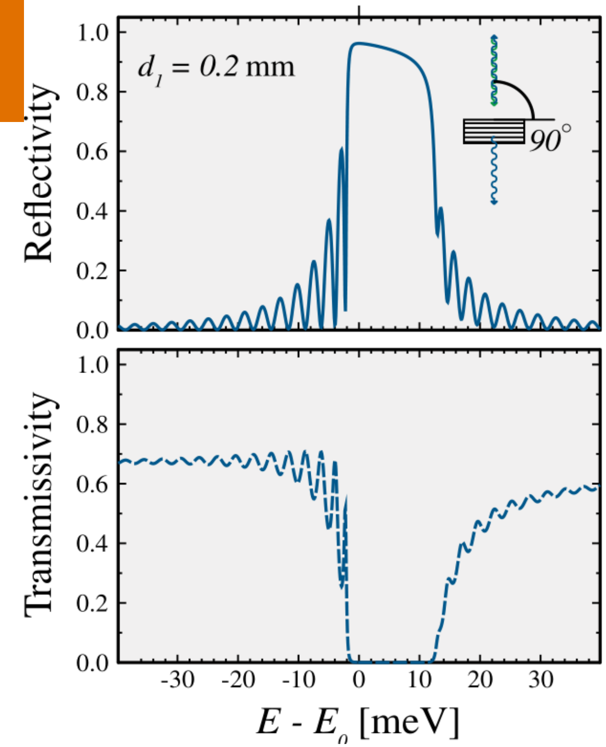
Outline

- What beam we want ?
- How to make it ?

X-ray FEL oscillator





Crystal response

~10 meV spectral acceptance

Proposed	R. Collela and A. Luccio (1984) K-J Kim, Y. Shvyd'ko, S. Reiche (2008)
Cavity tuning	R.M.J. Cotterill (1968); K-J Kim and Y. Shvyd'ko (2009)
Harmonic	H. X. Deng et. al (2012)

What kind of drive beam XFELO needs?

- High rep-rate, low energy spread, low emittance
- Narrow spectral acceptance → small correlated energy spread (flat chirp), relatively long bunch (~ps)
- KEK 3-GeV ERL: energy double to 6 GeV, radiation at 12.4 keV
- European XFEL 14.5 GeV, spent 4.9 kA beam, radiation at 12 keV
- LCLS-II 4 GeV beam, 5^{th} harmonic, radiation at 14.4 keV
- LCLS-II-HE 8 GeV beam, fundamental, radiation at 14.4 keV
- Also proposed at Shanghai

R. Hajima et. al., FEL2012, Nara, Japan, WEPD30

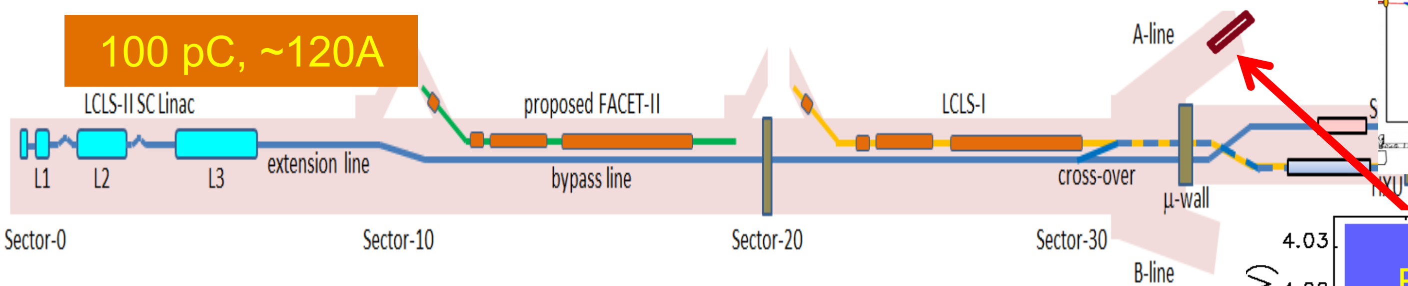
J. Zemella et. al., FEL2012, Nara, Japan, WEPD29

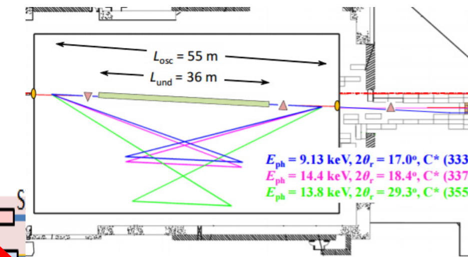
T. Maxwell et. al., IPAC2015, Richmond, VA, USA

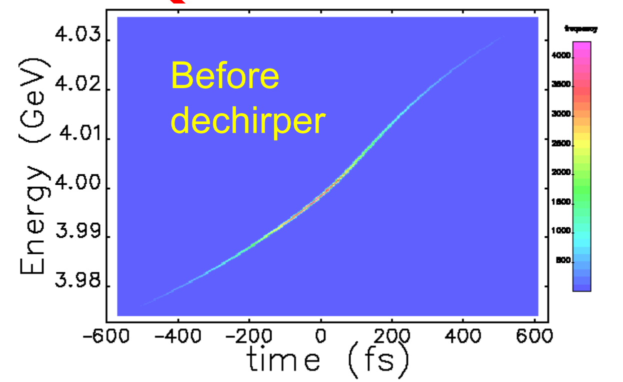
Talk by Haixiao

4 GeV LCLS-II SCRF linac driven 5th harmonic XFELO

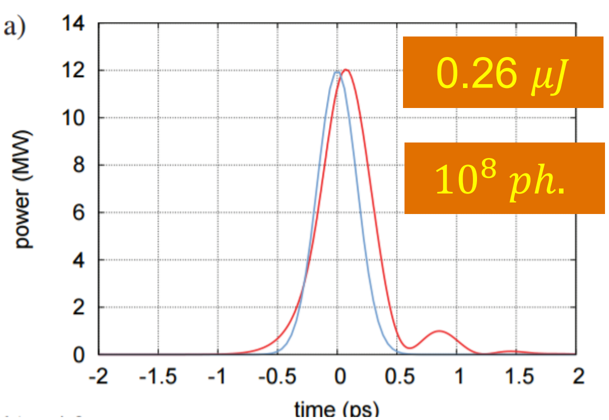
- 4 GeV beam direct to End Station A through Aline

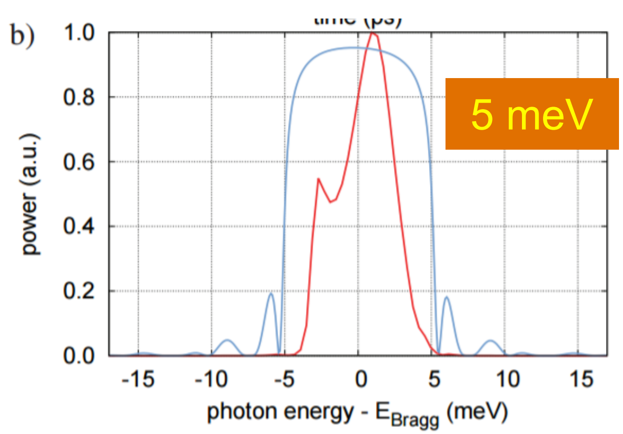


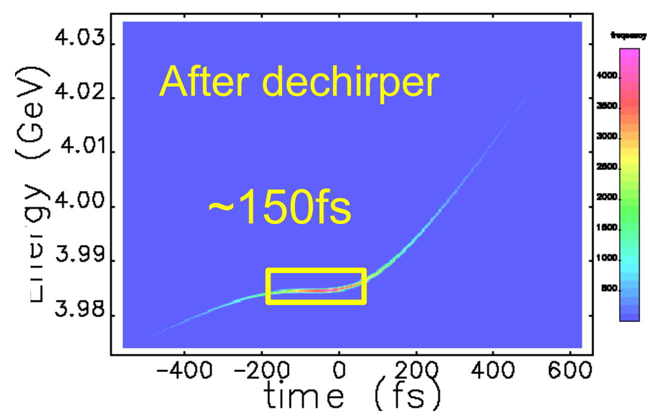




- Simulation with 400fs, 50pC ideal Gaussian beam



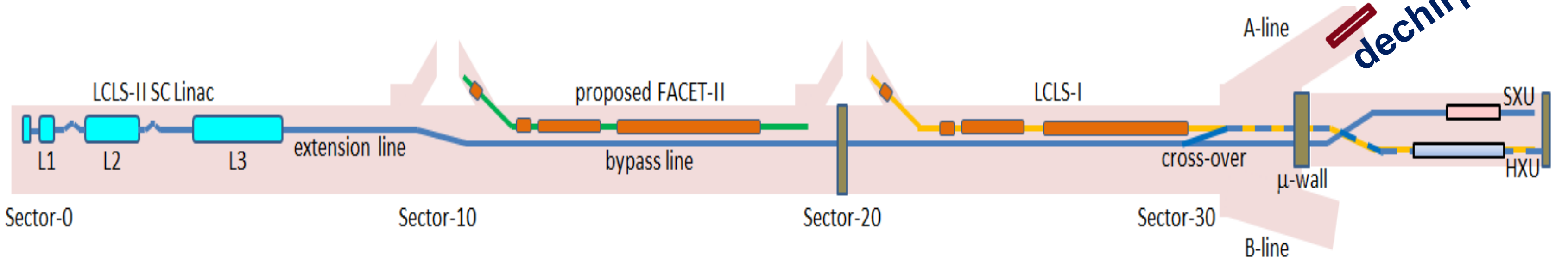




- However, wakefields induce large nonlinear chirp, only ~150 fs useful part

T. Maxwell et. al, IPAC2015 tupma028 *J. Zemella et. al, FEL2015 tup030*

Elements contribute to final phase space shape



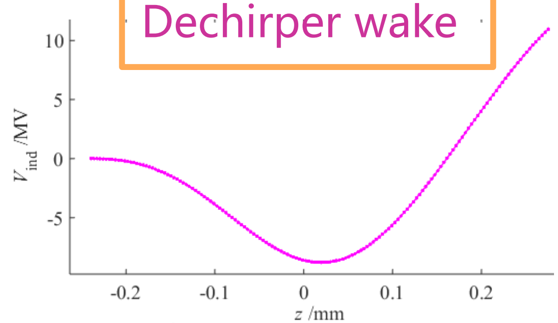
- RF
  - RF induces curvature in phase space
  - Determined by RF phase

Structure　　Current

$$W(s) = L_{\mathrm{acc}} \int_{-\infty}^{s} w(s - s')\lambda(s')ds'$$

- Wakefield
  - Cavities : weak
  - Long bypass : strong
  - Dechirper : strong

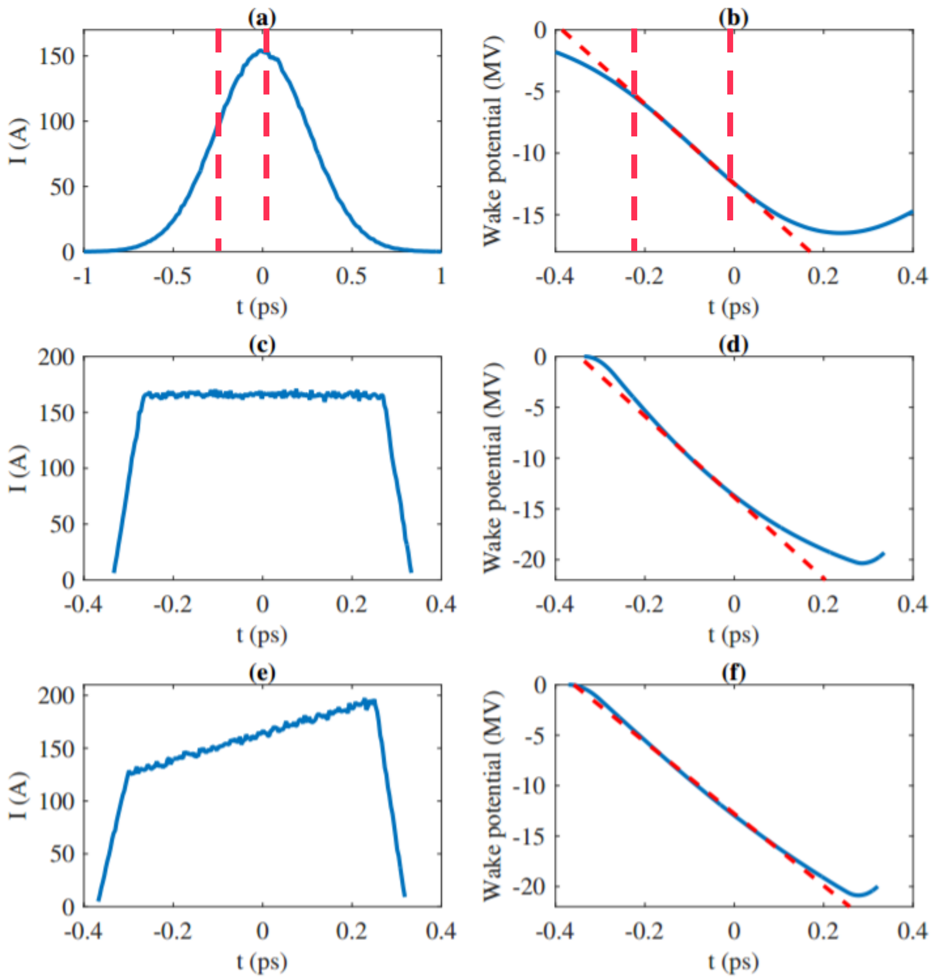
Dechirper wake



- RF phase, beam current, bunch compression and wakefields talk to each other.

- Bunch compression
  - Determined by input phase space curvature and R56, T566, U5666

Wake induced loss: L3 + 2 km bypass + dechirper



$$W(s) = L_{\mathrm{acc}} \int_{-\infty}^{s} w(s - s')\lambda(s')ds'$$

- Assumed same FWHM of three current profile and same dechirper parameters
- Ramped current can largely linearize the overall wake induced loss

Shaping the current ?

Weilun Qin et. al, IPAC2016 WEPOY019

Assume ramp current at injector exit [Elegant]

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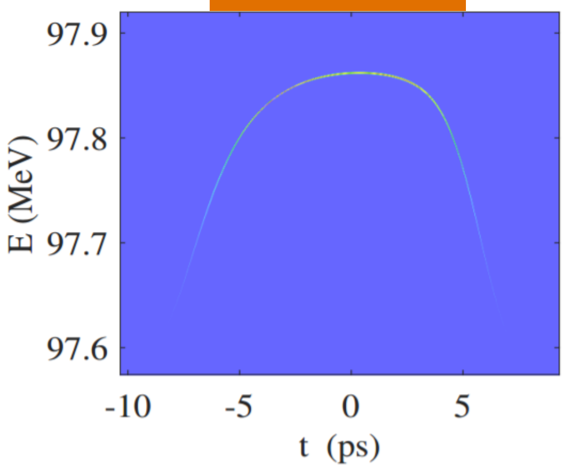
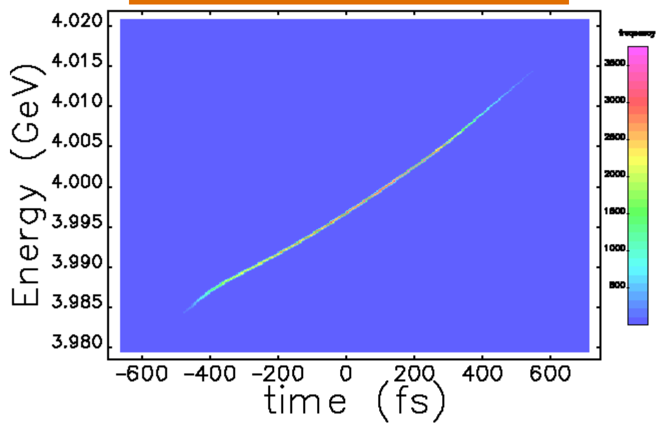
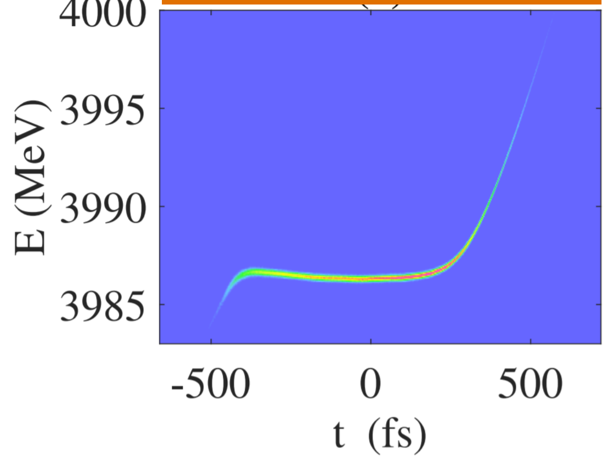
Before L1

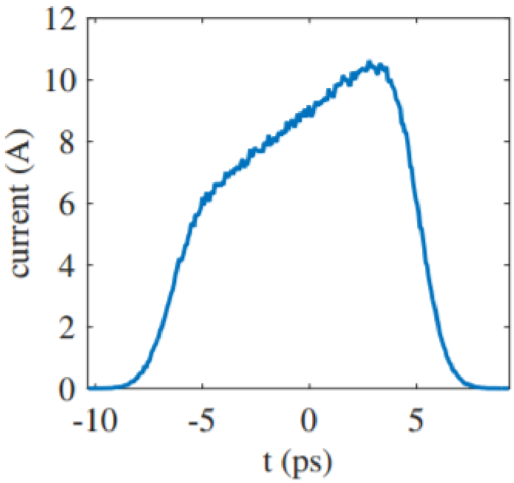


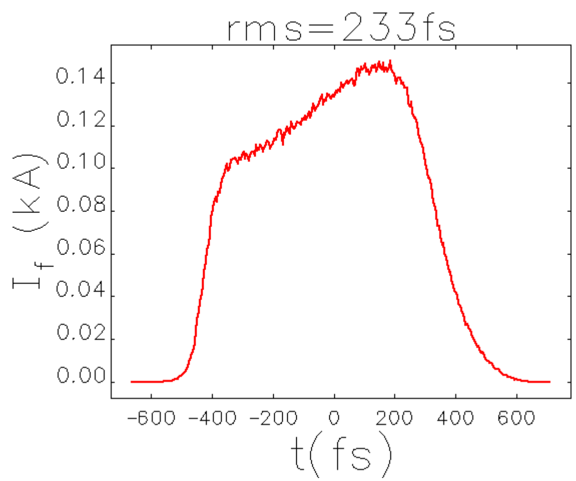
Before dechirper



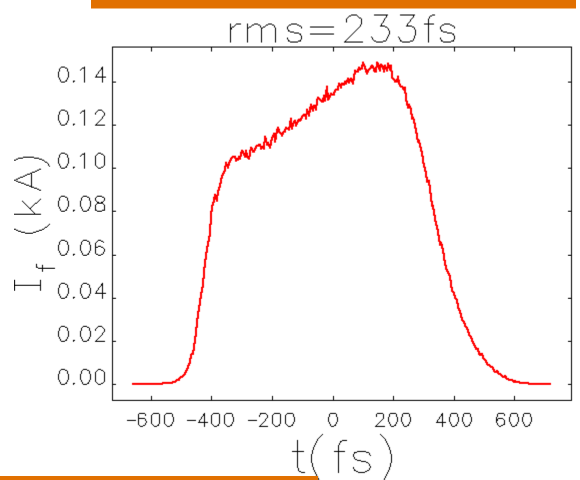
After dechirper







Over 500fs flat chirp



LINAC parameters not changed

Weilun Qin et. al, IPAC2016 WEPOY019

A more global scope: how to make a ramp (flat energy chirp)

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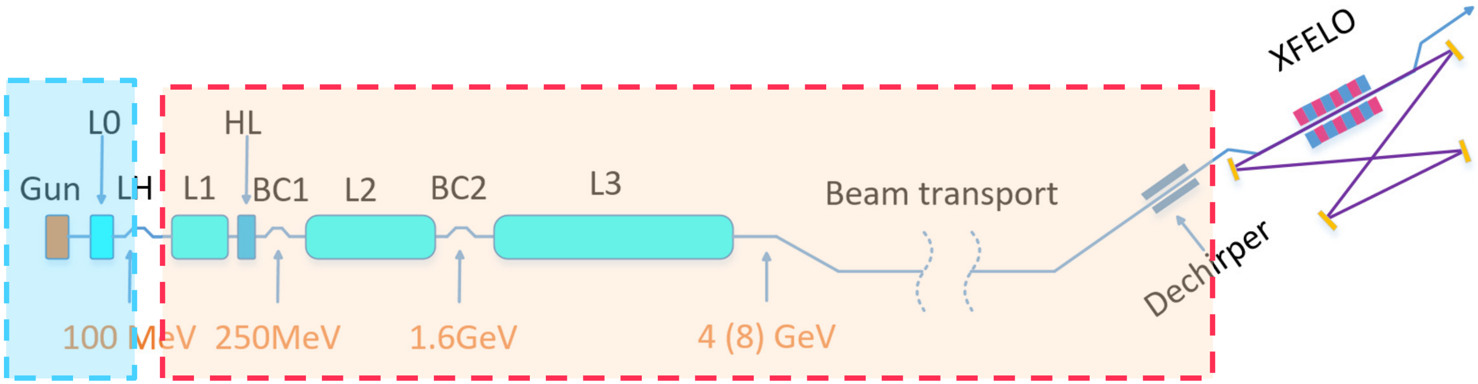
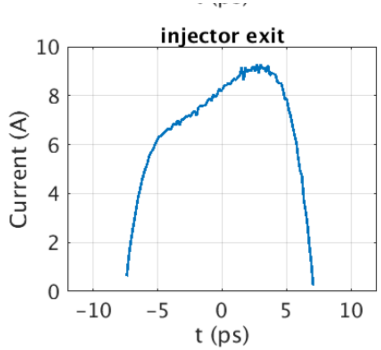
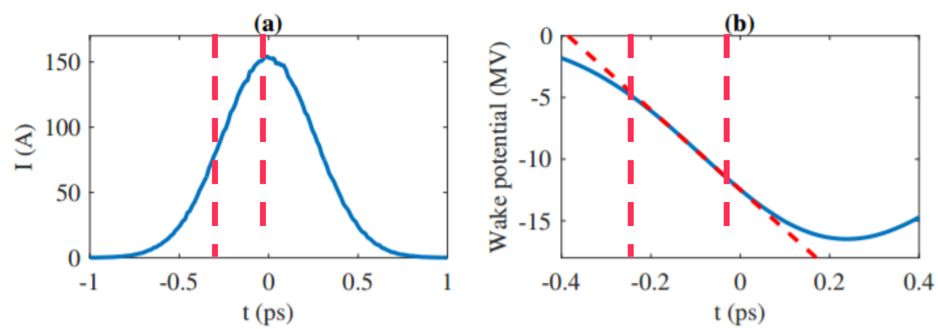


Shaping the injector laser

and/or

Optimizing the LINAC



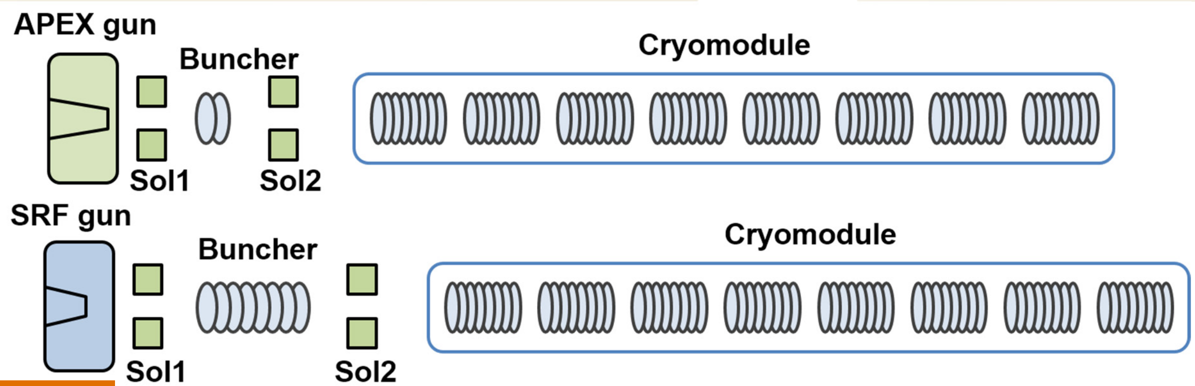


Injector	Linac	XFELO
ASTRA	LiTrack & Elegant	Ginger

Two injector setups

APEX gun, w/o shaping

SRF gun, w/ shaping

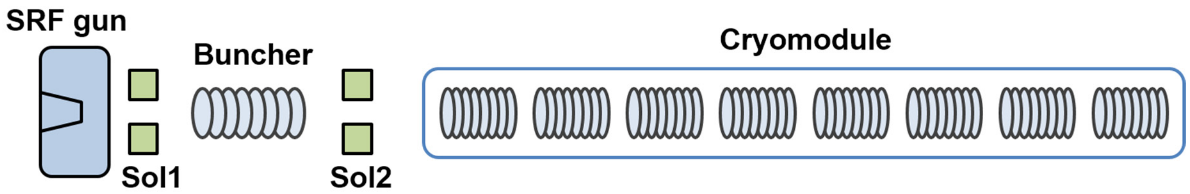


Layout from C. Mitchell (APEX) & R. K. Li (SRF)

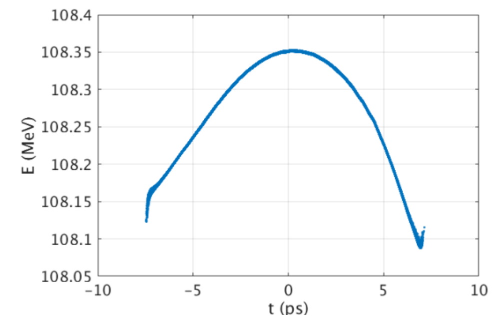
	APEX gun	SRF gun
f_0 (MHz)	186	200
L_{gap} (cm)	4	15
E_a (MV/m)	20	40
E_{gun} (MeV)	0.75	4.1
ε_{intri} (mrad)	1.0	
Q (pC)	100	
t_{laser} (ps)	40	20
ε_n, 100% (mm-mrad)	**0.30**	**0.25**

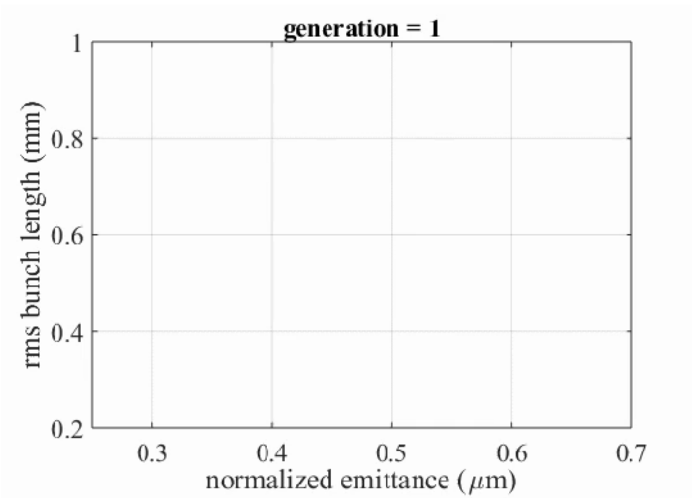
- Higher gun exit energy with SRF gun (~4.1 MeV), easier to control the emittance growth due to drive laser shaping.
- Lower emittance with higher gun gradient

Injector: SRF gun optimization



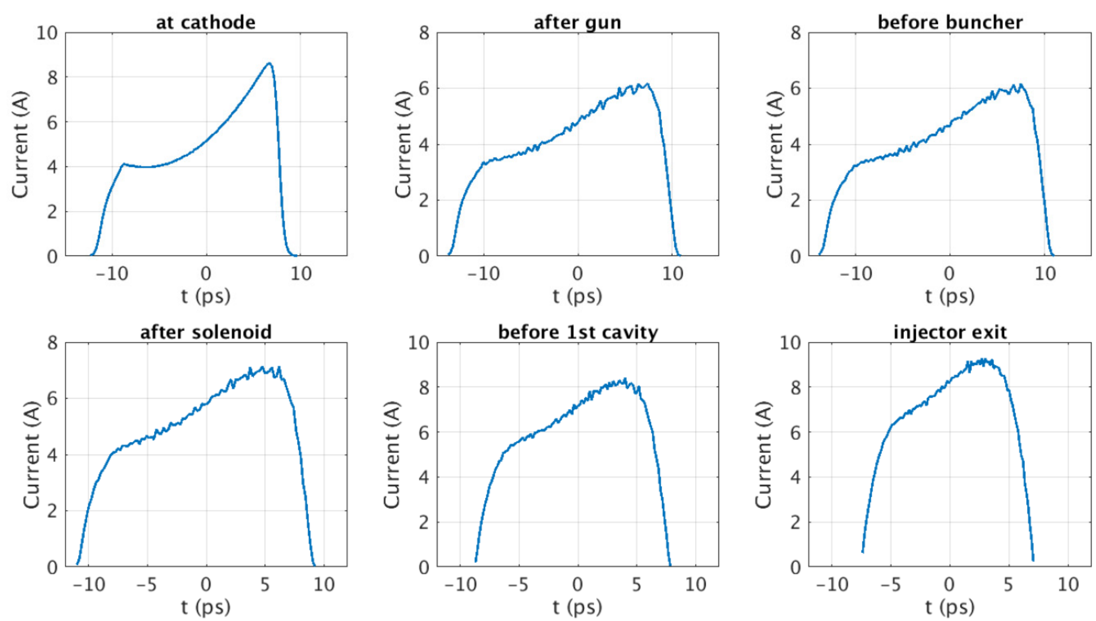
Phase space at injector exit





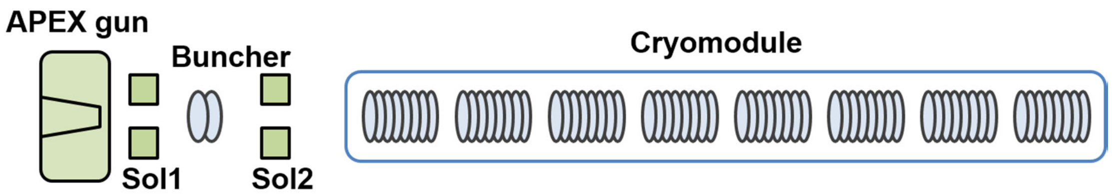
Emittance and bunch length

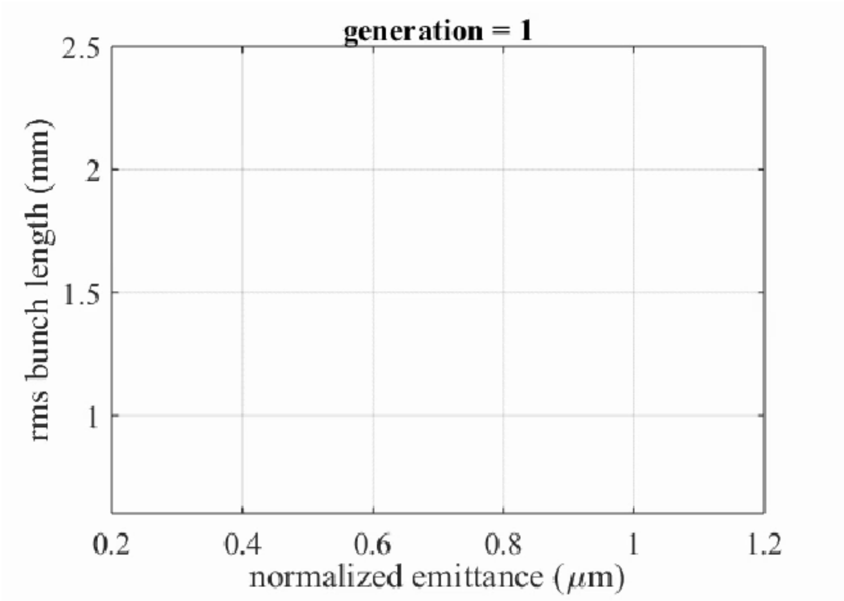
Current evolution in the injector



Optimization with 10k macroparticles
Full simulation with 1M macro particles

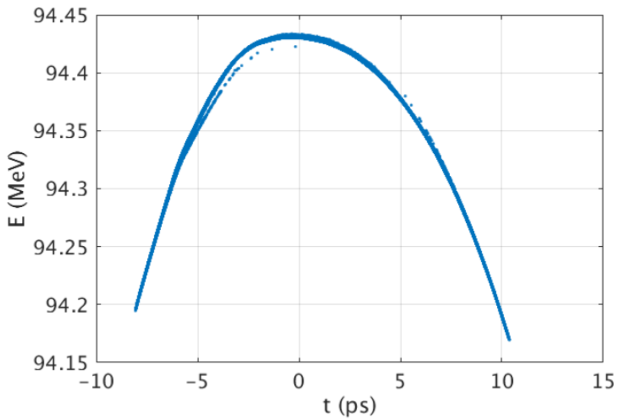
Injector: APEX gun optimization



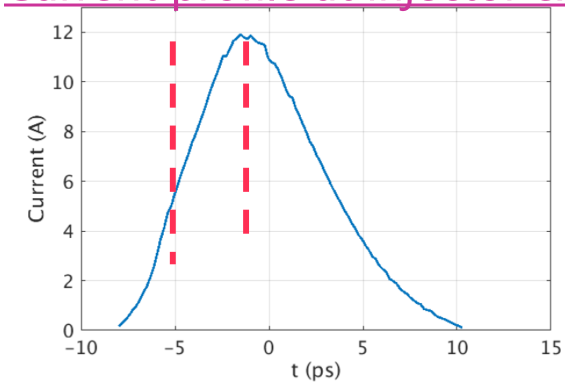


Emittance and bunch length

Phase space at injector exit

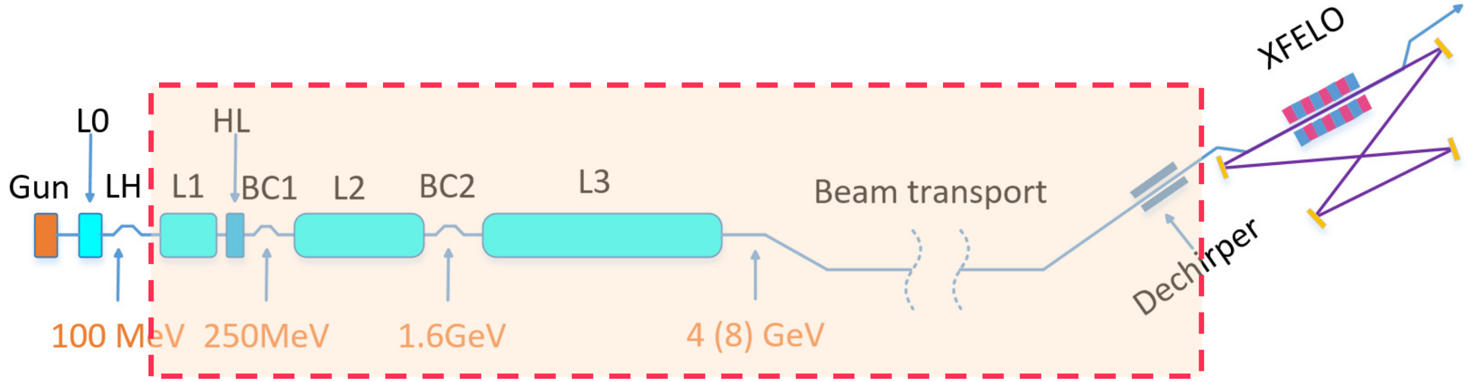


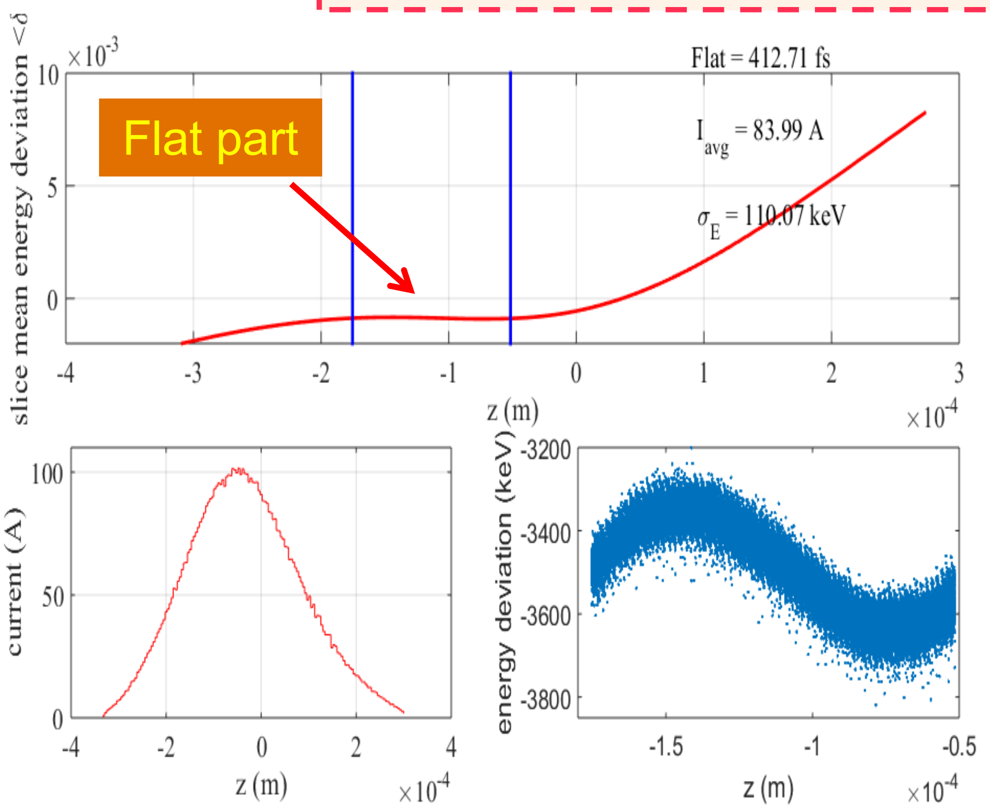
Current profile at injector exit



Optimization with 10k macroparticles
Full simulation with 1M macro particles

Fast LINAC optimizer





- LiTrack integrated with MOGA (MATLAB)
- Objectives
  - Flat length, length within 0.2 MeV energy spread
  - Average beam current within flat length
- Fix L1, L2, L3 energy

Linac optimization for APEX gun setup (4 GeV)

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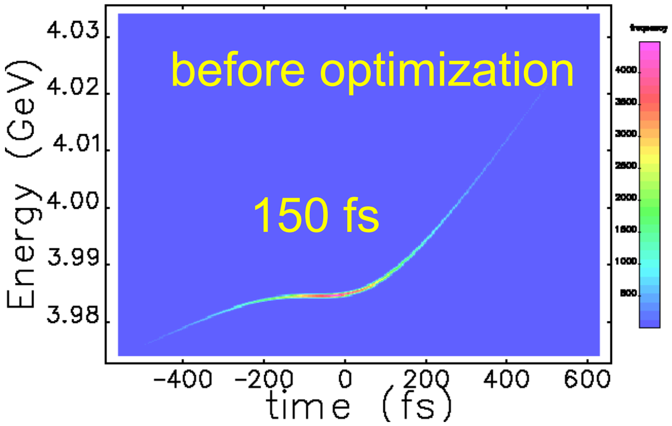
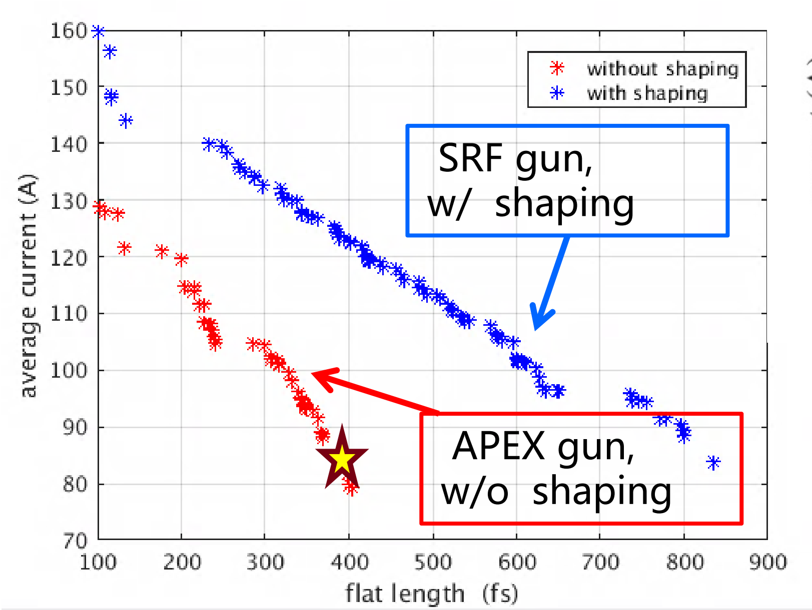
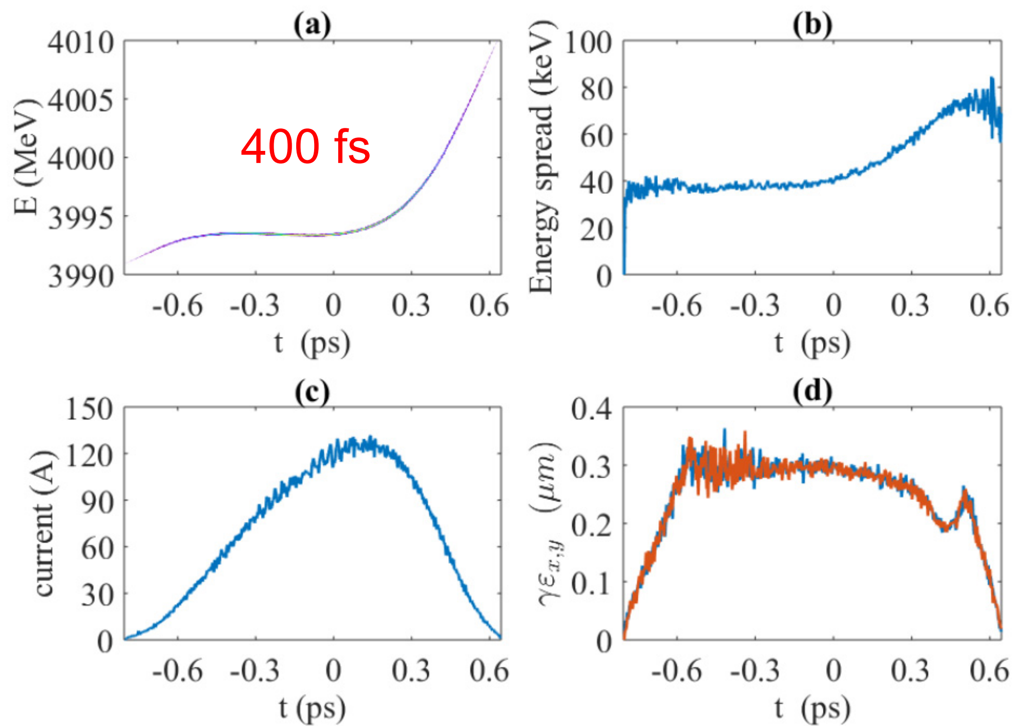




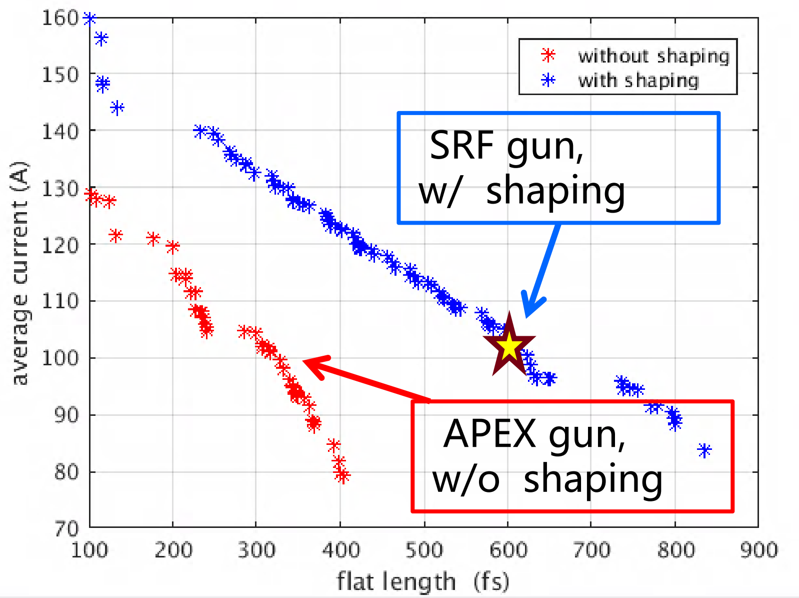
APEX gun output @ undulator entrance



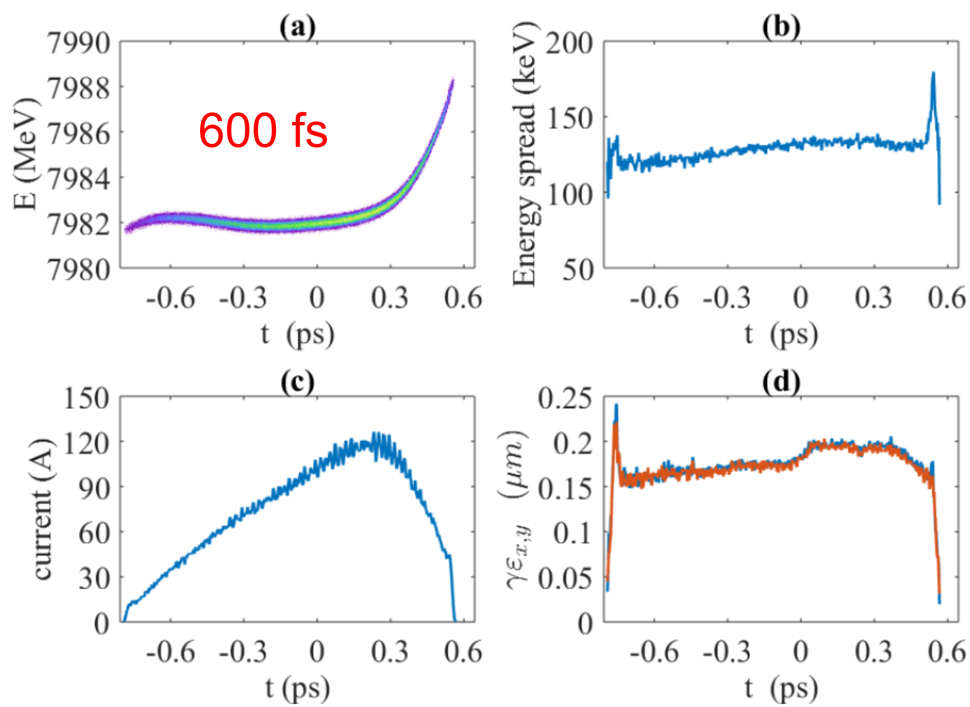
- about 400 fs flat part, 120 A peak current
- Low slice emittance and slice energy spread
- Projected energy spread 0.07%

Linac optimization for SRF gun setup (8 GeV)

- With shaping & SRF gun
  - about twice useful charge in the flat part
  - better emittance
  - Higher energy spread (injector current lower than APEX)



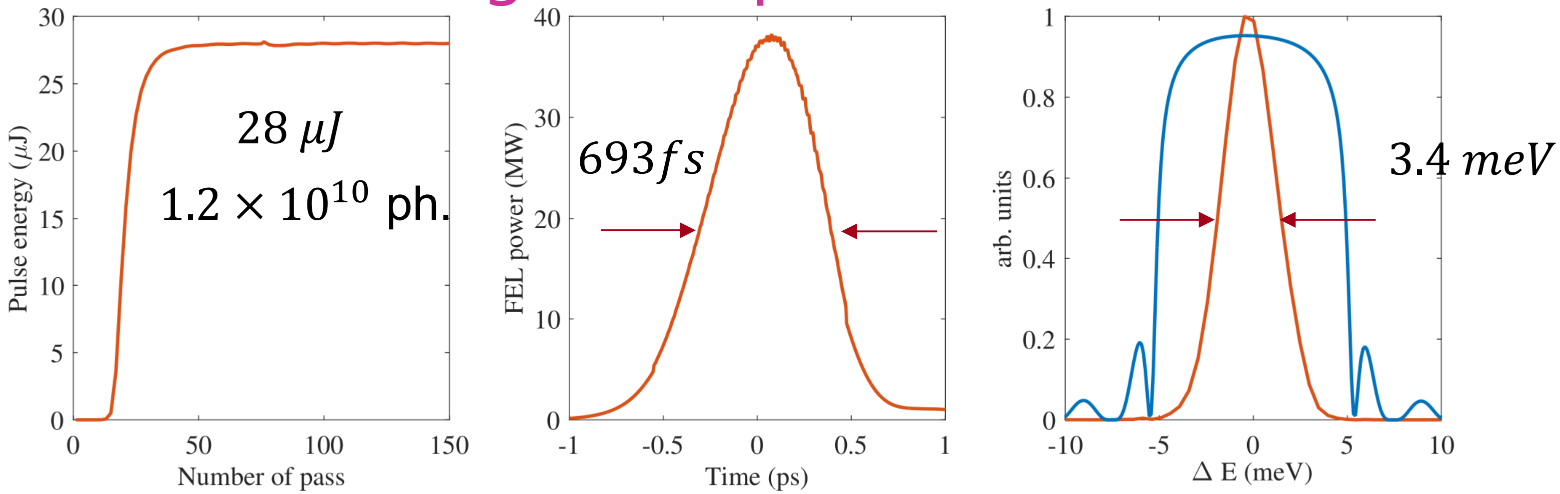
SRF gun output @ undulator entrance



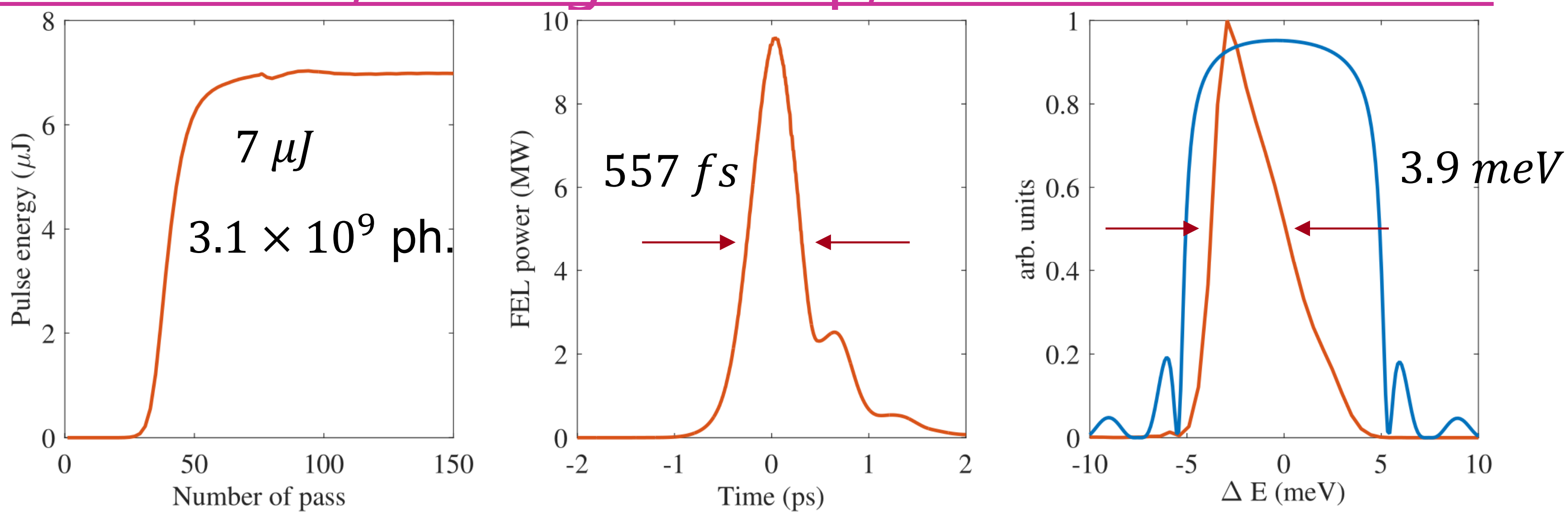
- Over 600 fs flat part, 120 A peak current
- Low slice emittance and slice energy spread
- Projected energy spread 0.02%

XFELO performance at 14.4 keV [GINGER]

- 8 GeV beam, SRF gun setup, fundamental XFELO



- 8 GeV beam, APEX gun setup, fundamental XFELO



XFELO performance at 5 – 25 keV [GINGER]

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Table 1: XFELO simulation parameters and output pulse properties (the repetition rate is assumed to be 1 MHz).

Parameter	**4.9 keV**	**10 keV**	**14.4 keV**	**14.4 keV**	**14.4 keV**	**20 keV**	**24.2 keV**
Electron gun	SCRF	SCRF	NCRF	NCRF	SCRF	SCRF	SCRF
FEL K	3.2128	2.0125	1.4304	1.4837	1.4837	1.0125	1.1539
E_{beam} [GeV]	7.982	7.982	3.994	7.982	7.982	7.982	7.982
ε_n [μm]	0.25	0.25	0.35	0.35	0.25	0.25	0.25
σ_E [keV]	130	130	70	70	130	130	130
λ_u [cm]	2	2	2.6	2	2	2	1.5
N_u	1000	1000	1250	1000	1000	1000	2000
harmonic number	1	1	5	1	1	1	1
Z_R [m]	10	10	10	10	10	10	15
Bragg crystal	C(220)	C(440)	C(733)	C(733)	C(733)	C(880)	C(888)
Output coupling	4%	4%	4%	4%	4%	4%	5%
Pulse energy [μJ]	3.1	21	0.3	7	28	11	4.4
Spectral FWHM [meV]	10.9	5.4	5.8	3.9	3.4	2.7	1.3
Temporal FWHM [fs]	138	530	400	557	693	905	1989
$\sigma_\tau \sigma_\omega$ (FWHM)	2.27	4.37	3.52	3.26	3.58	3.67	4.06
# of Photons/pulse	3.9×10^9	1.3×10^{10}	1.3×10^8	3.1×10^9	1.2×10^{10}	3.4×10^9	1.1×10^9
Spectral flux [ph/s/meV]	3.6×10^{14}	2.4×10^{15}	2.2×10^{13}	7.9×10^{14}	3.6×10^{15}	1.3×10^{15}	8.5×10^{14}

Conclusions

- XFELO requires long flat chirp in the longitudinal phase space. Dechirper and bypass wakefields results in large nonlinear chirp in the longitudinal phase space, only ~150 fs useful part.
- We optimized the LINAC parameters to get over 400fs useful part for APEX gun setup. With SRF gun & injector laser shaping, we managed to get longer useful part and more useful charge.
- With this start-to-end beam, Ginger simulations show that $10^{9} \sim 10^{10}$ photons/pulse can be obtained for 5-25 keV photons with ~meV bandwidth.

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