Design of an LPA-Based First-Stage Injector for Synchrotron Light Sources

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Acknowledgements

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Dr. Dazhang Li	(IHEP)	Dr. Fei Li	(UCLA)	(Tsinghua Univ.)
Dr. Ming Zeng	(IHEP)			
Mr. Jia Wang	(IHEP)			

Outlines

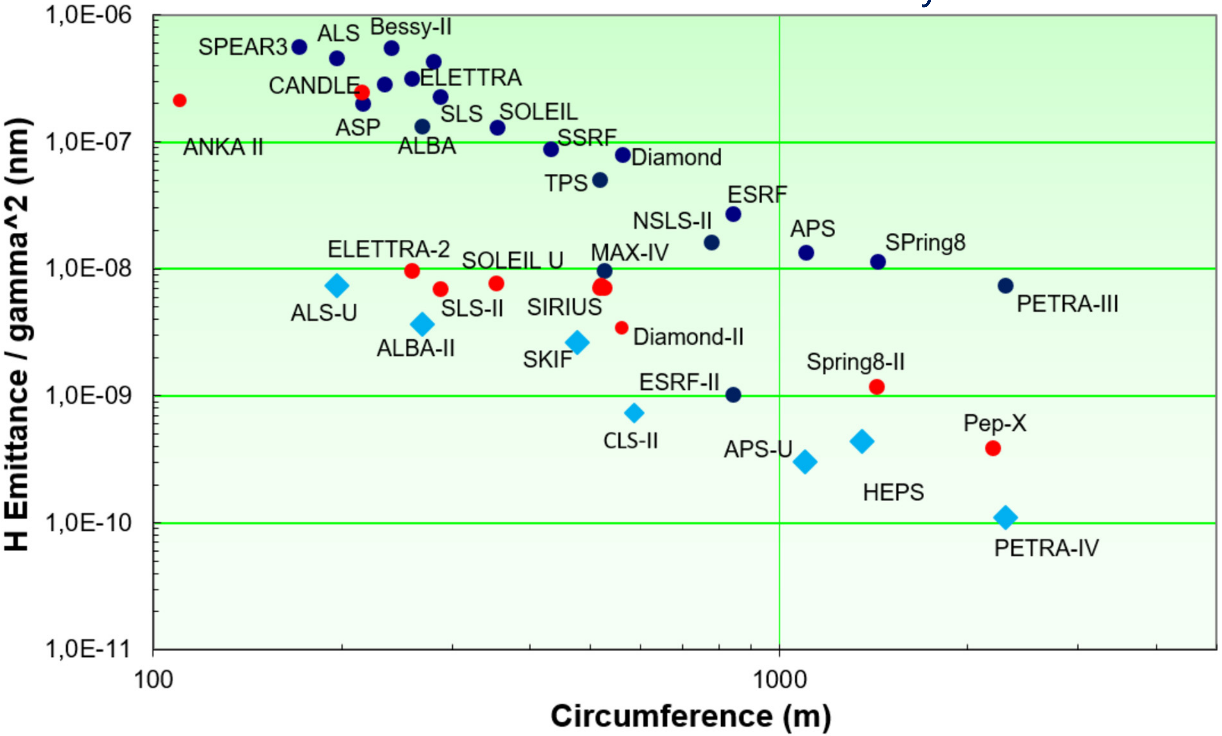
1. Introduction
2. A Preliminary Design
3. Summary and Outlook

1. Introduction

Synchrotron Light Sources

- Synchrotron light source is a kind of widely used tool for researches in different fields.
- Many synchrotron light sources are in operation as well as many new projects and upgrade projects are under design, or construction.

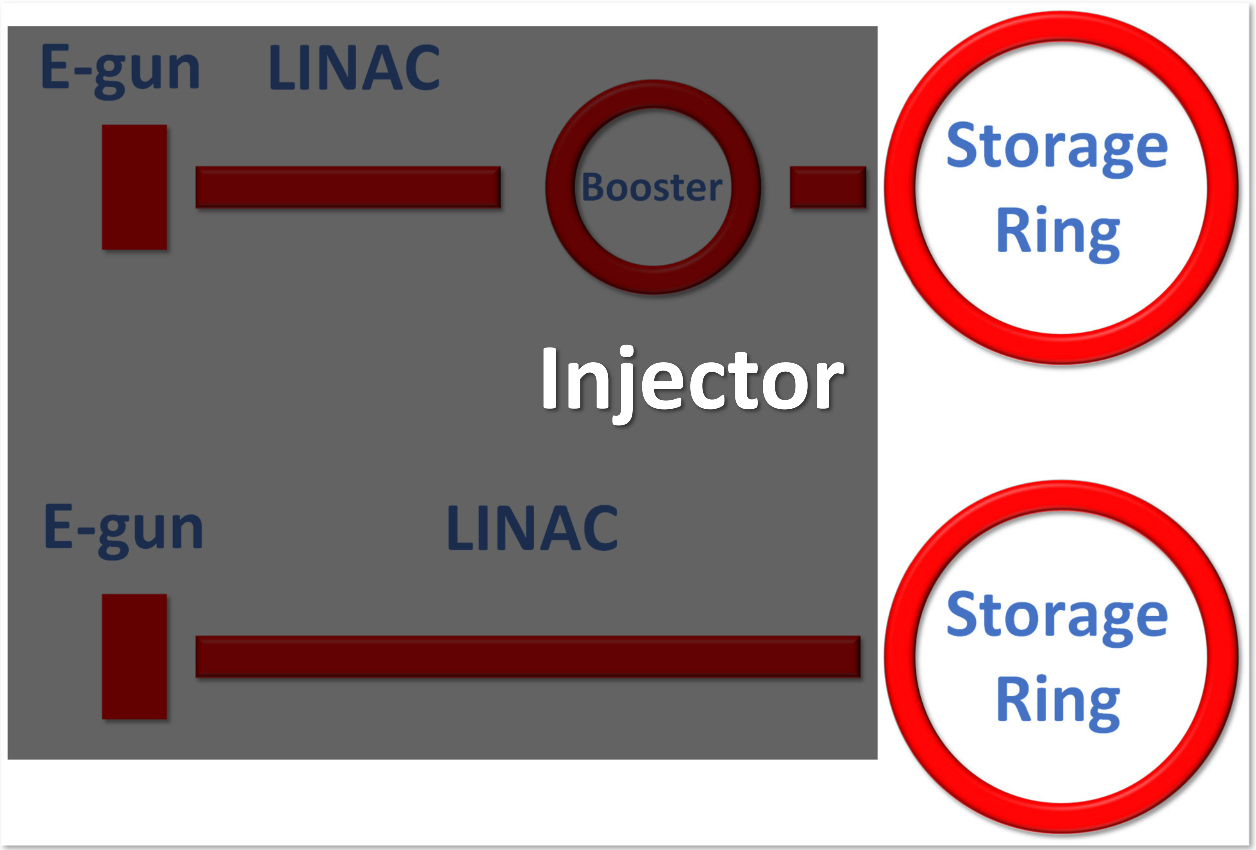
Courtesy of R. Bartolini



R. Bartolini, Overview of ongoing 4th generation light source projects worldwide, in the 7th Diffraction Limited Storage Rings Workshop, April 12th, 2021

Synchrotron Light Sources

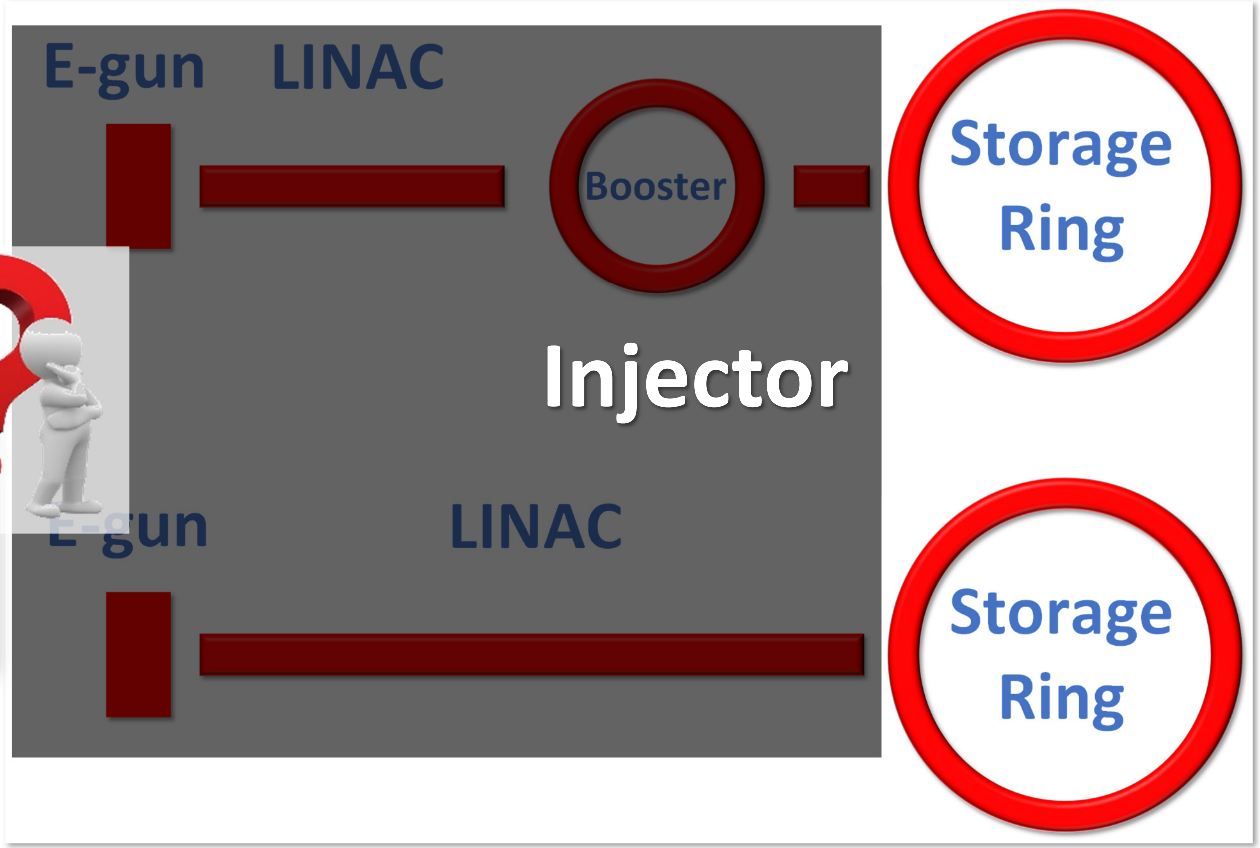
- Accelerator Chains of Synchrotron Light Sources
  - Electron Gun
  - LINAC
  - (Booster)
  - Storage Ring



Synchrotron Light Sources

- Whether laser plasma accelerator can be used to replace the injector of **storage rings**?

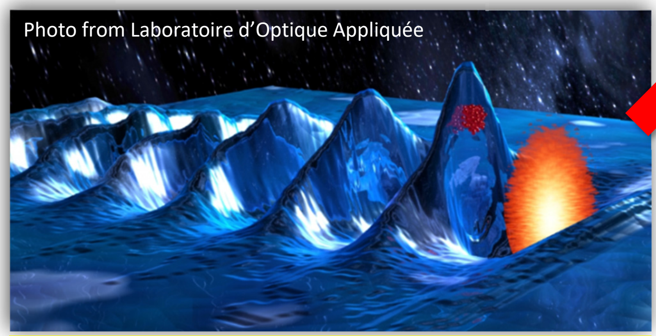
Laser Plasma Accelerator



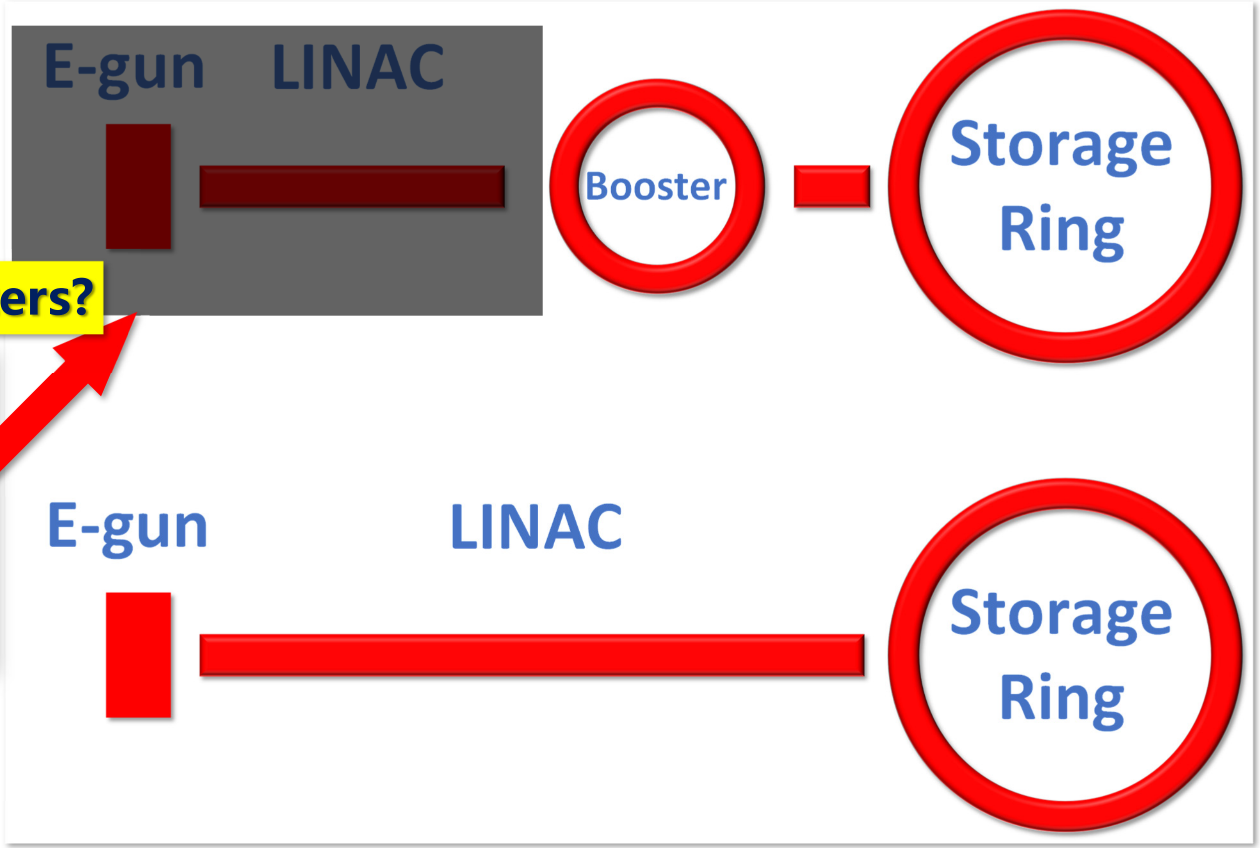
https://loa.ensta-paris.fr/research/upx-research-group/laser-wakefield-acceleration-lwfa/

Synchrotron Light Sources

- Whether laser plasma accelerator can be used to replace the injector of ~~storage rings~~? **boosters?**



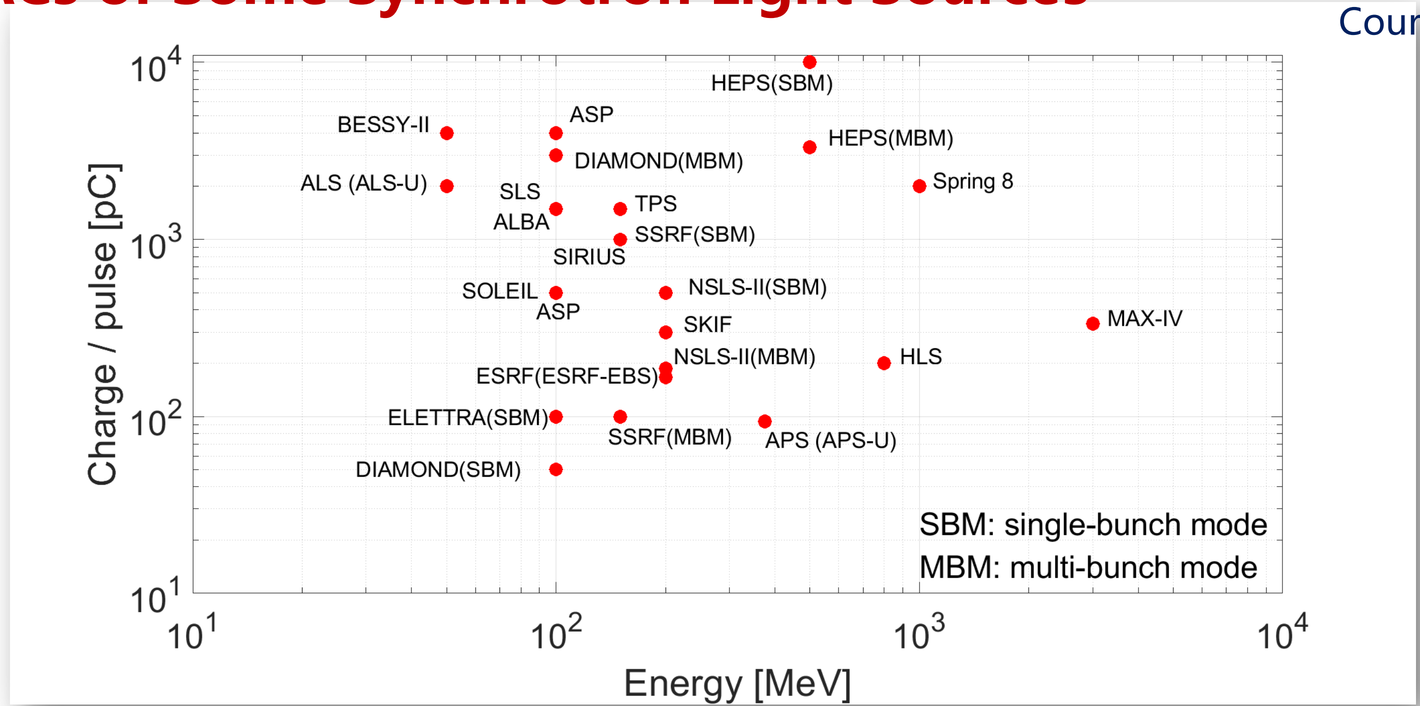
Laser Plasma Accelerator



https://loa.ensta-paris.fr/research/upx-research-group/laser-wakefield-acceleration-lwfa/

LINACs of Some Synchrotron Light Sources

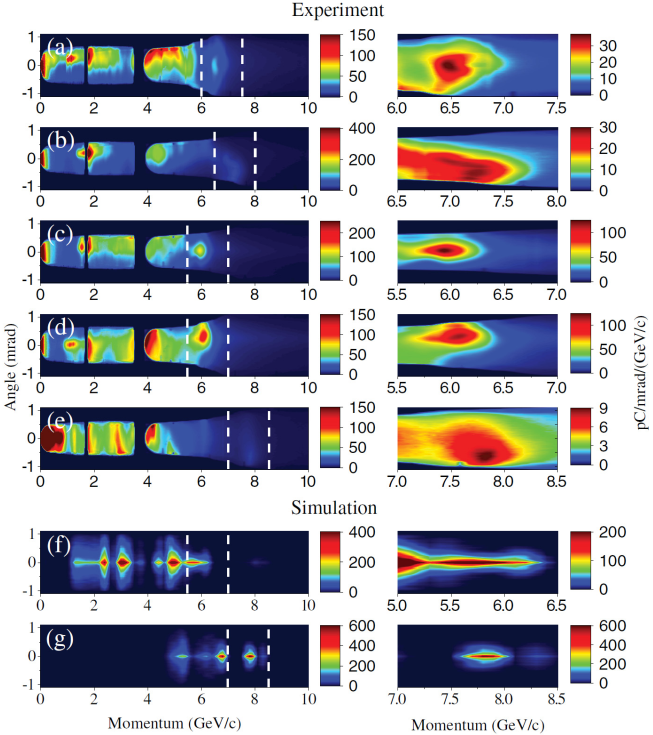
Courtesy of C. Meng



- Beam Energy : ~ hundreds MeV
- Bunch Charge : ~ hundreds pC – ~ nC
- Energy Stability & Energy Spread : designed energy ± several percent

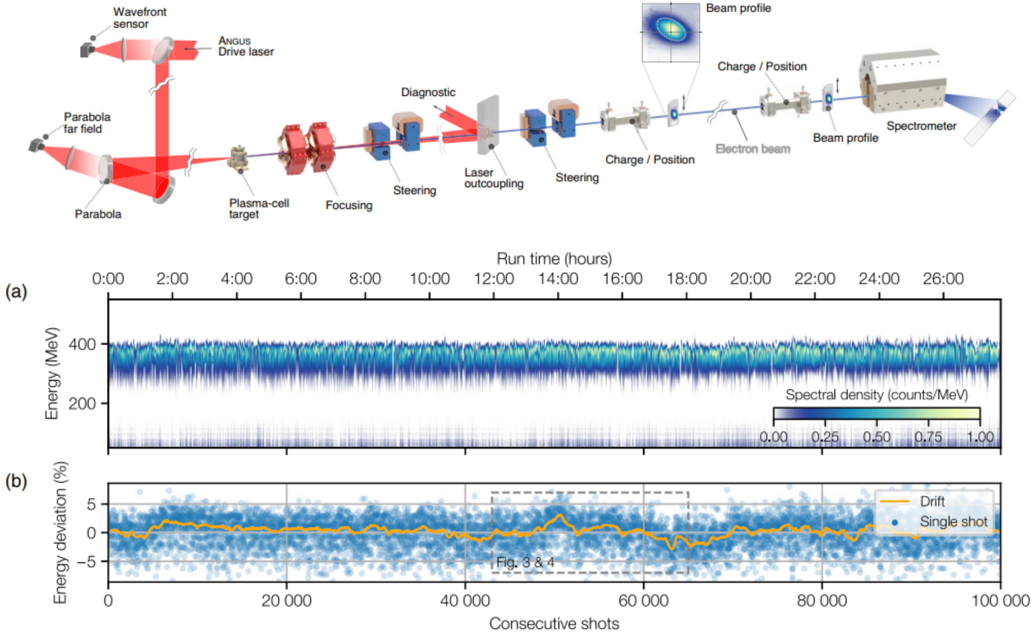
Achieved Parameters of LPAs

electron beams up to **7.8 GeV**



A. J. Gonsalves et al. Phys. Rev. Lett. 122, 084801 (2019)

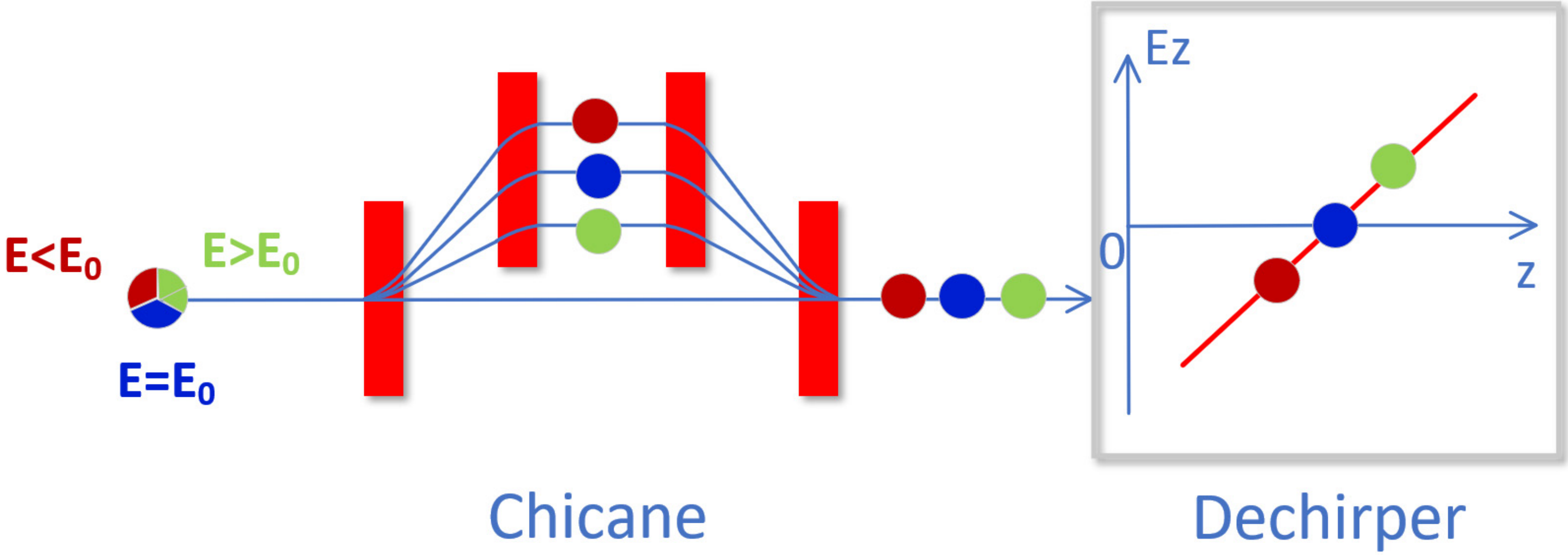
stable 24-h operation: 100,000 consecutive electron beams



- a peak energy of 368 MeV (2.4% rms);
- a charge of 25 pC (11% rms);
- a FWHM energy spread of 54 MeV (15 MeV rms).

Andreas R. Maier et al. Phys. Rev. X 10, 031039 (2020)

Basic Principle

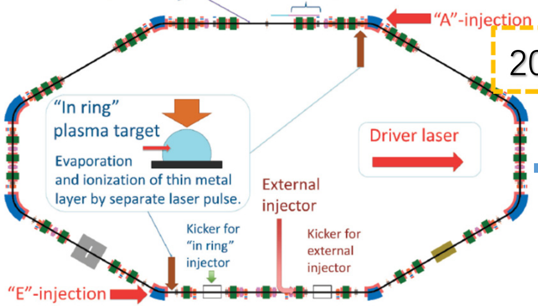


- A. He et al., Phys. Rev. ST Accel. Beams 18, 014201 (2015)
- S. Di Mitri, Bunch-length Compressors, in CERN-2018-001-SP (CERN, Geneva, 2018)
- S. A. Antipov et.al. Phys. Rev. Accel. Beams. 24.111301 (2021)
- A. Ferran Pousa et.al. arXiv:2106.04177 (2021)

Some Previous Work

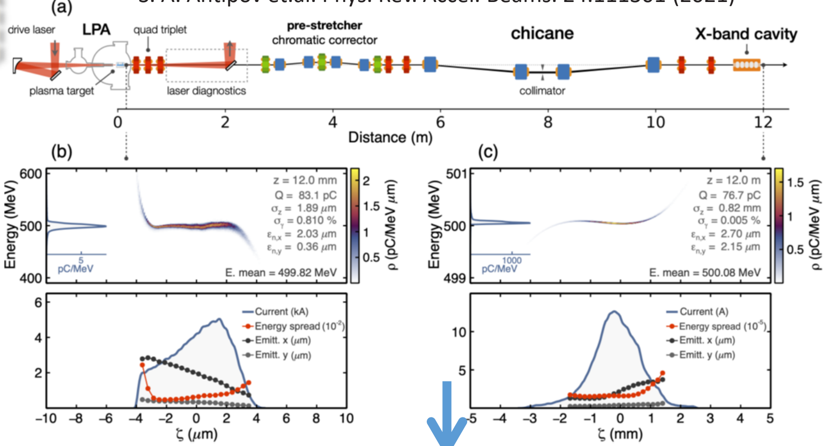
2017, IOTA

Aleksandr Romanov, AIP Conference Proceedings 1812, 040012 (2017)



2021, PETRA IV

S. A. Antipov et.al. Phys. Rev. Accel. Beams. 24.111301 (2021)



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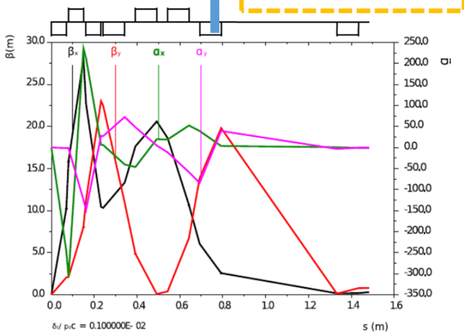
2014, ANKA



S. Hillenbrand et al. Nuclear Instruments and Methods in Physics Research A 740 (2014) 153–157

2017, DIAMOND

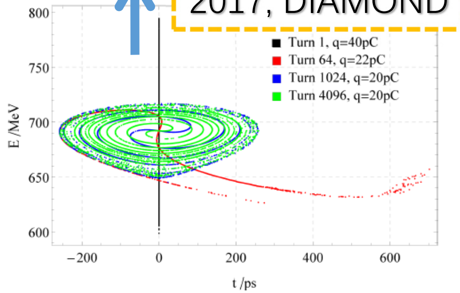
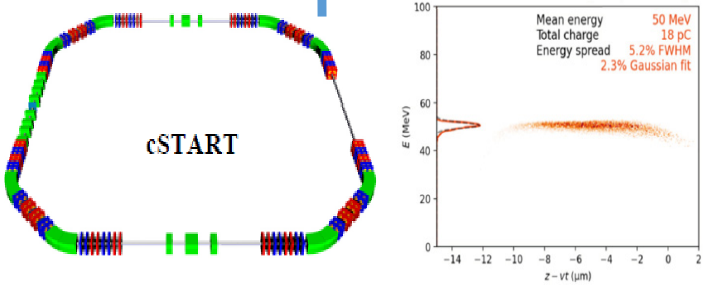


Figure 1: Evolution of the longitudinal phase space for a 0.7 GeV laser-derived electron bunch in DIAMOND.

K. A. Dewhurst et al. TUPIK036, in Proceedings of IPAC2017, Copenhagen, Denmark

2021, KIT



E. Panofski et al. TUPAB163, in Proceedings of IPAC2021,Campinas, SP, Brazil

Some Previous Work

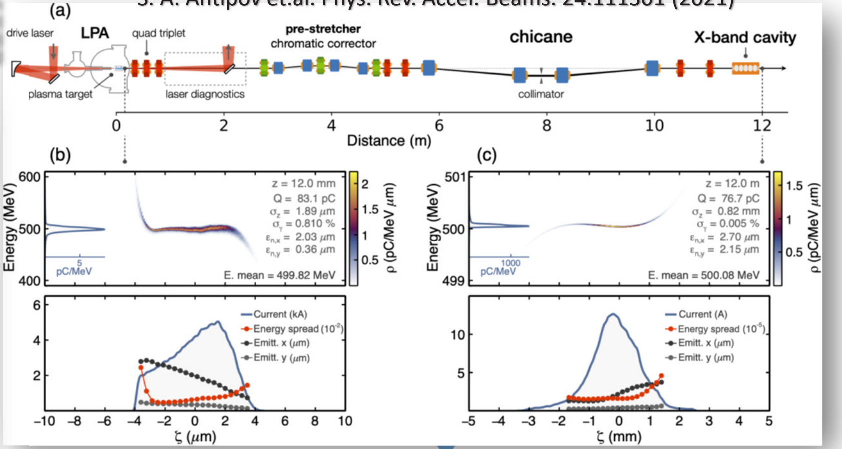
2021, PETRA IV

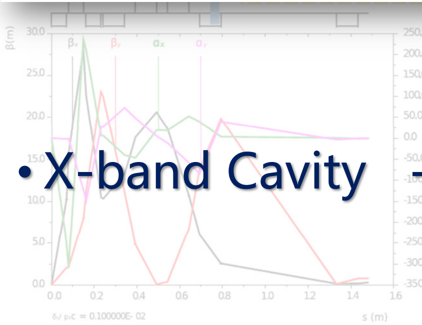
Aleksandr Romanov, AIP Conference

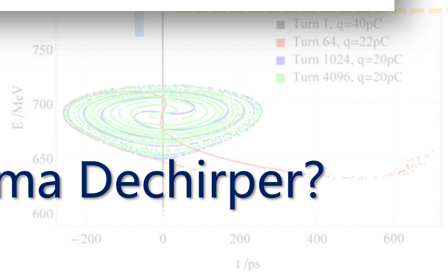
TABLE I. Beam parameters at the entrance and at the exit of the beam line.

Parameter	Plasma cell exit	Final
Twiss α (x,y)	−0.47, −0.42	1.35, 1.01
Twiss β (x,y)	3.1, 3.0 mm	14.5, 48.4 m
Norm. ϵ (x, y)	2.0, 0.4 μm	2.7, 2.1 μm
Charge	83 pC	77 pC
Length σ_z	2.0 μm	0.8 mm
Energy spread σ_γ	0.8×10^{-2}	0.5×10^{-4}

S. A. Antipov et.al. Phys. Rev. Accel. Beams. 24.111301 (2021)







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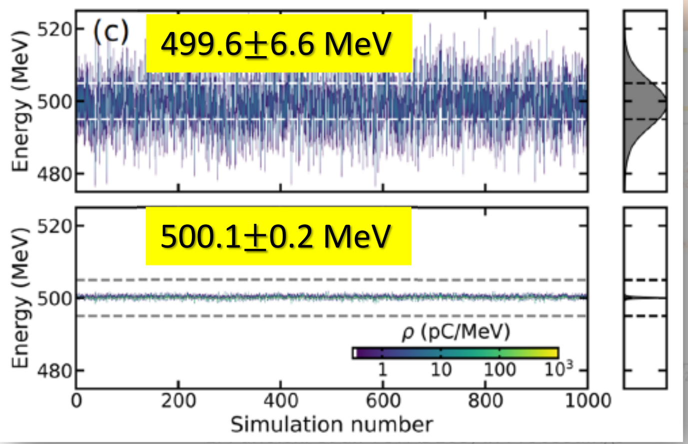


- X-band Cavity -> Plasma Dechirper?

S. Hillenbrand et al. Nuclear Instruments and Methods in Physics Research A 740 (2014) 153–157

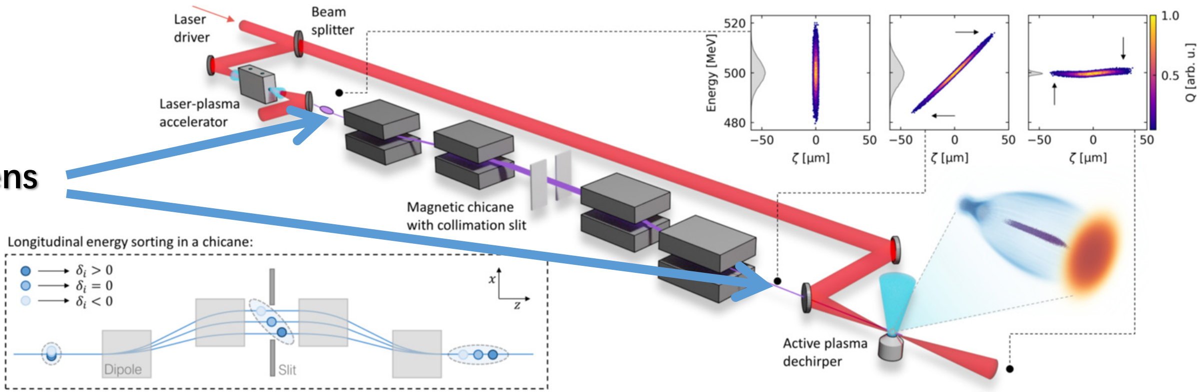
K. A. Dewhurst et al. TUPIK036, in Proceedings of IPAC2017, Copenhagen, Denmark

of IPAC2021,Campinas, SP, Brazil

Chicane + Active Plasma Dechirper

A. Ferran Pousa et.al. arXiv:2106.04177 (2021)

Active Plasma Lens



Beam Parameters	Unit	Values (10 pC)		Values (50 pC)
		Initial	Final	Final
Central Energy	MeV	500		
Charge	pC	10		50
Central Energy Jitter	-	1%	0.024%	0.074%
Energy Spread	-	1%	0.10%	0.43%

- Chicane + Active Plasma Dechirper -> higher charge?

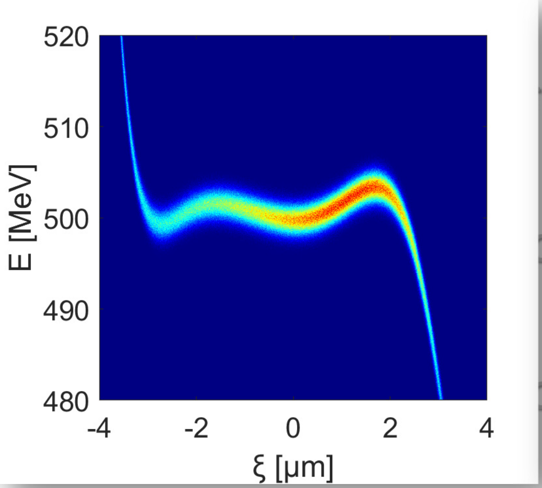
2. A Preliminary Design

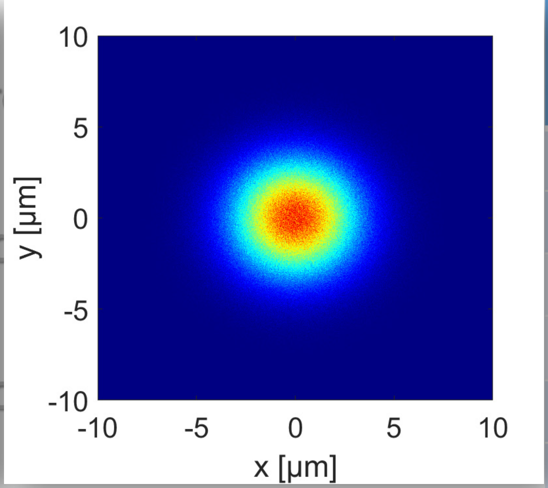
Basic Layout

- LPA : Laser Plasma Accelerator
- Triplet : Provide transverse focusing
- Chicane : Add energy chirp
- APD : Active Plasma Dechirper

Basic Layout

- LPA : Laser Plasma Accelerator

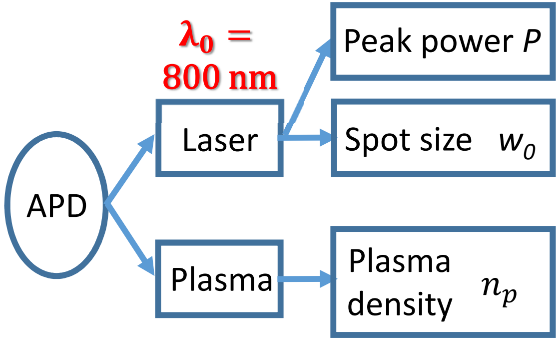




Main Parameters of Generated Electron Beam	Unit	Value
Central Energy	MeV	500
Charge	pC	50-200
RMS Energy Spread σ_δ	%	0.94
Normalized Emittance $\epsilon_{n,r}$	μmrad	2
RMS Bunch Length σ_z	μm	2
RMS Beam Size σ_x / σ_y	μm	2.2

- M. Kirchen, et al. Phys. Rev. Lett. 126, 174801 (2021).
- S. A. Antipov et.al. Phys. Rev. Accel. Beams. 24.111301 (2021)

Parameters Selection



$P\uparrow$ vs. $P\downarrow$

Trade-off ①: higher price & difficulty vs. lower dechirping strength

$w_0\downarrow$ vs. $w_0\uparrow$

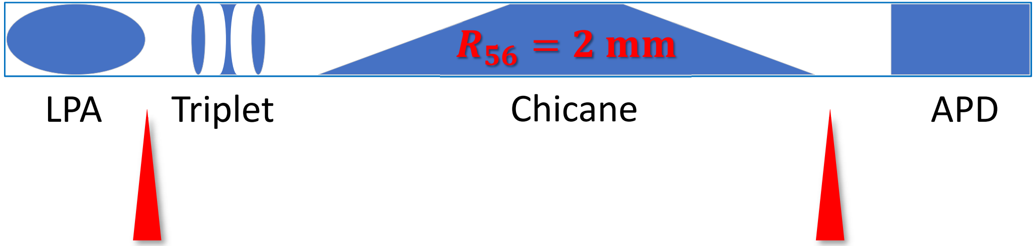
Trade-off ②: smaller electron beam size vs. lower dechirping strength

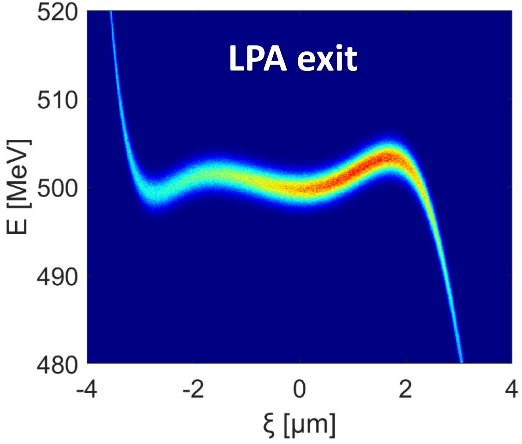
$n_p\uparrow$ vs. $n_p\downarrow$

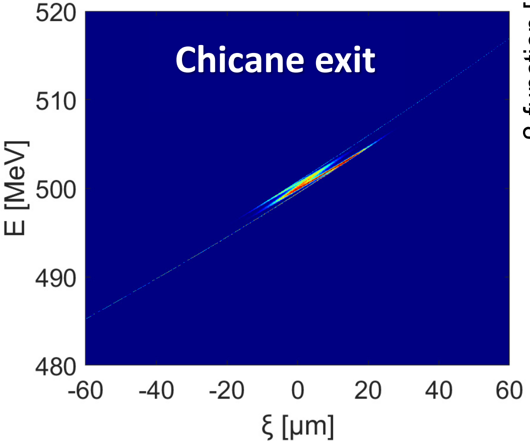
Trade-off ③: shorter electron bunch length vs. lower dechirping strength

- laser peak power: $\mathbf{P} = \frac{\pi}{4} c\epsilon_0 w_0^2 \left(\frac{2\pi a_0 m_e c^2}{\lambda_{laser} e}\right)^2 \propto \boldsymbol{w_0^2 a_0^2 = 150\ \mathrm{TW}}$
- peak normalized vector potential $\boldsymbol{a_0 = 2}$, nonlinear regime
- laser spot size: $\boldsymbol{w_0 = 33.4\ \mu m}$
- Plasma density: $\boldsymbol{n_{p,APD} = 2.5 \times 10^{16}\ cm^{-3}}$ → • Chicane $\boldsymbol{R_{56} = 2\ \mathrm{mm}}$

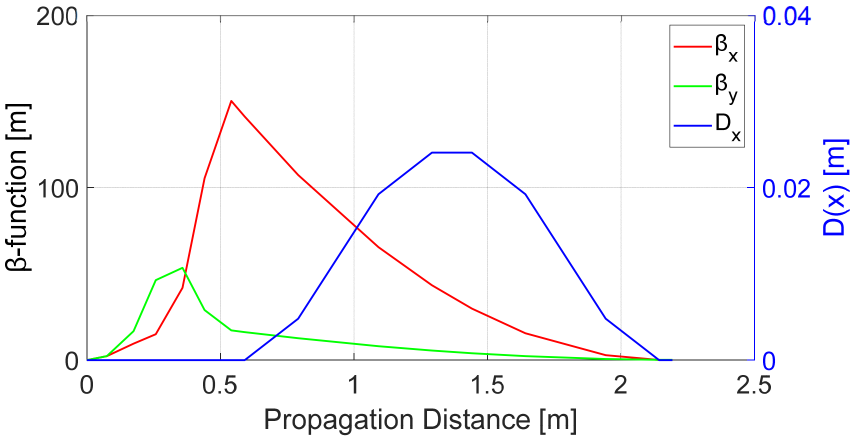
Beam Transfer Line Design (Twiss Matching)





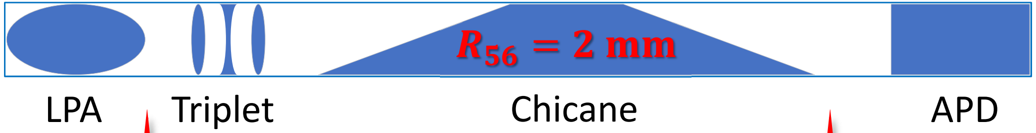


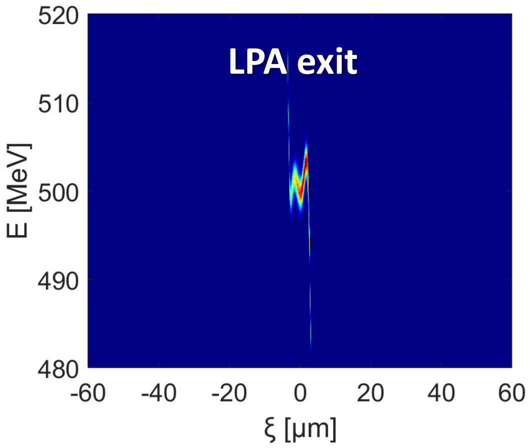
- Twiss parameters along the beamline

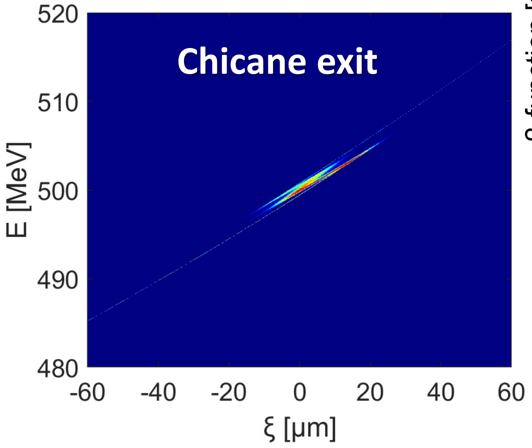


Parameters	Unit	Initial	Final
$\epsilon_{n,x}$ / $\epsilon_{n,y}$	μm	2.0/2.0	20.6/8.1
β_x / β_y	mm	2.4/2.4	61.2/173.9

Beam Transfer Line Design (Twiss Matching)







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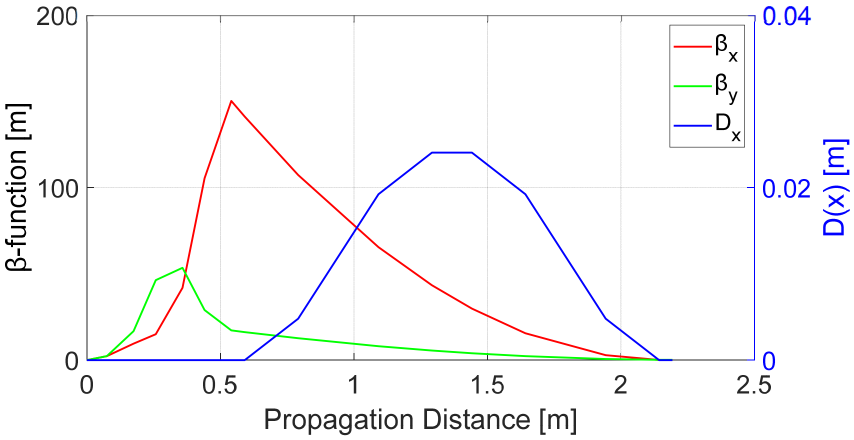

Parameters	Unit	Initial	Final
$\epsilon_{n,x}$ / $\epsilon_{n,y}$	μm	2.0/2.0	20.6/8.1
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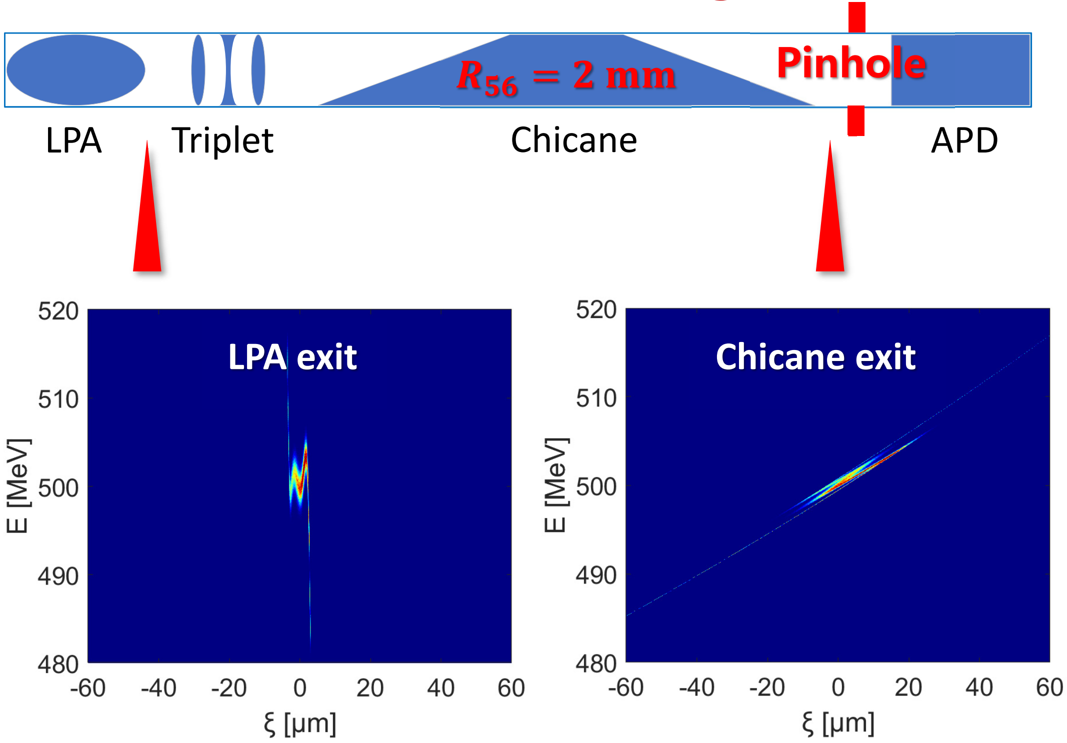
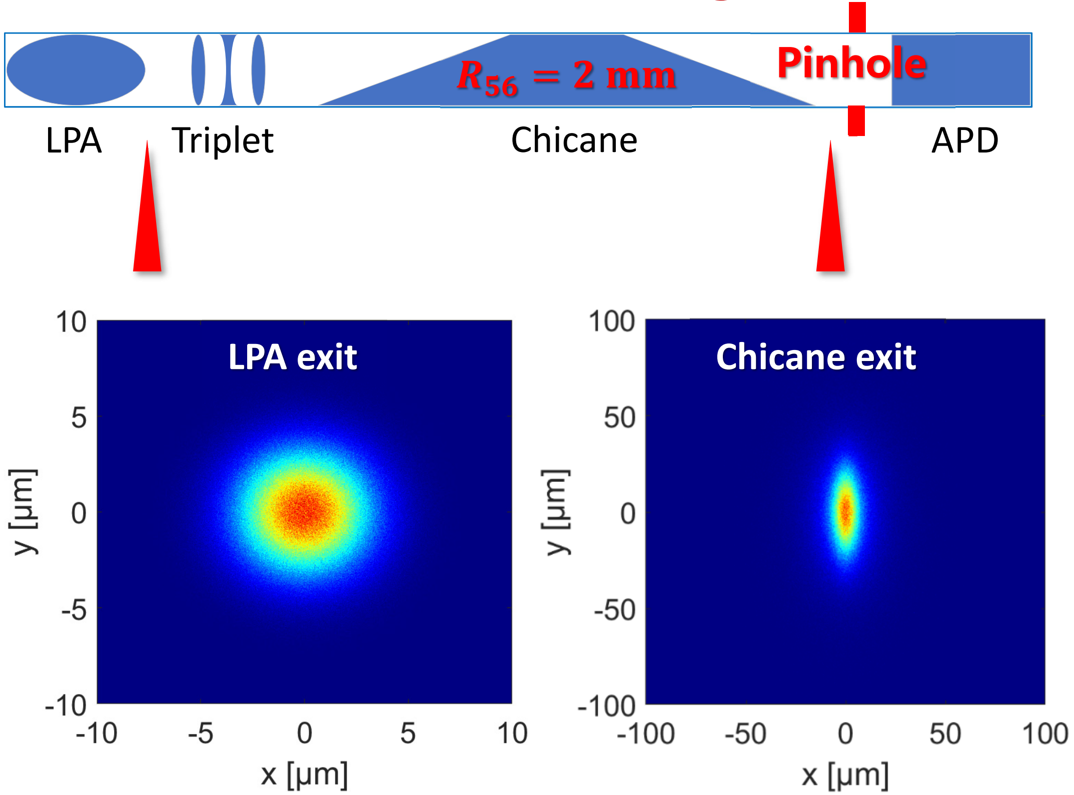
Beam Transfer Line Design (Pinhole)



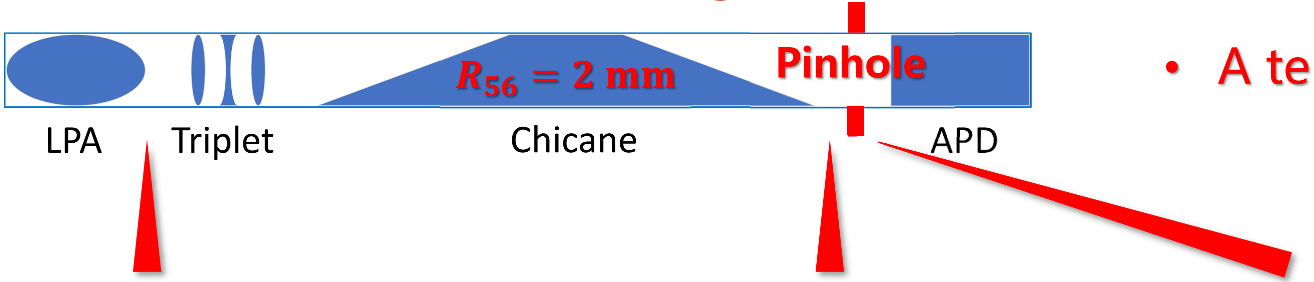
- A tentative solution

Beam Transfer Line Design (Pinhole)

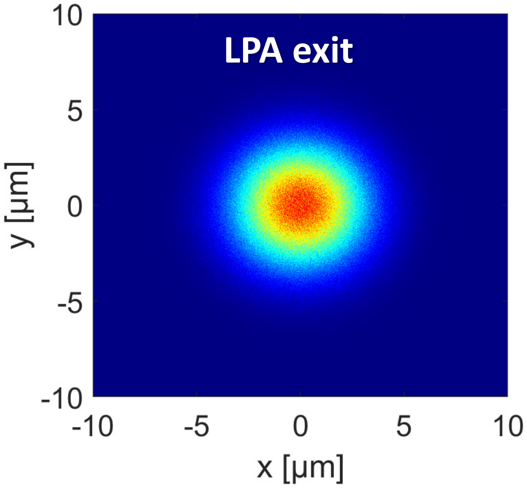


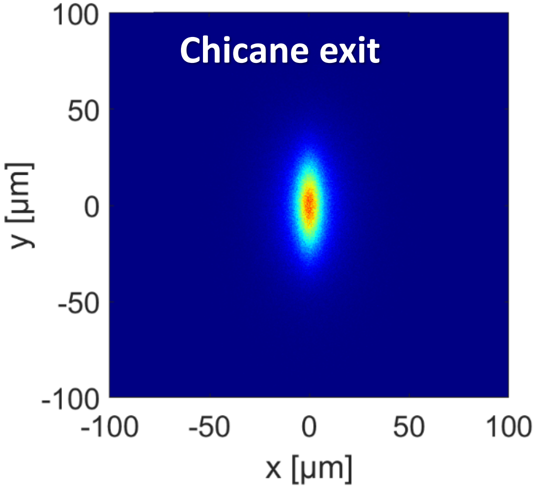
- A tentative solution

Beam Transfer Line Design (Pinhole)

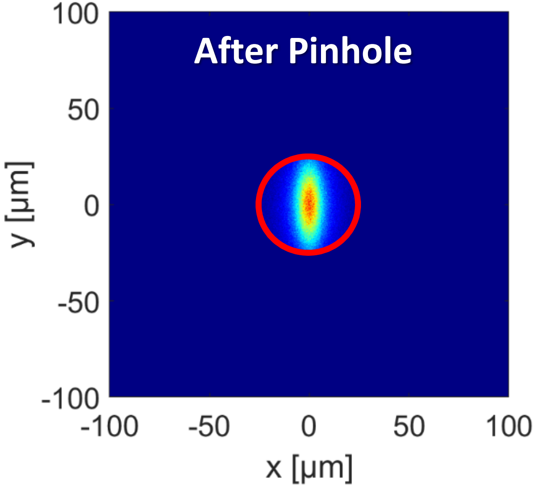


- A tentative solution

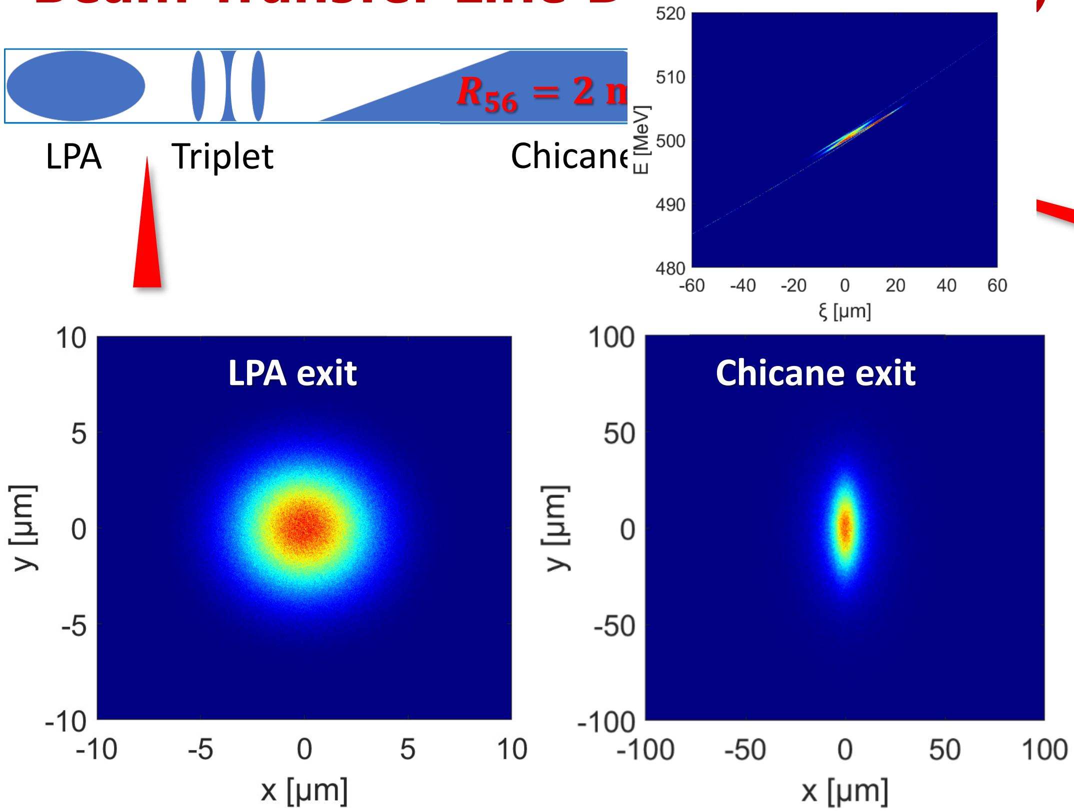




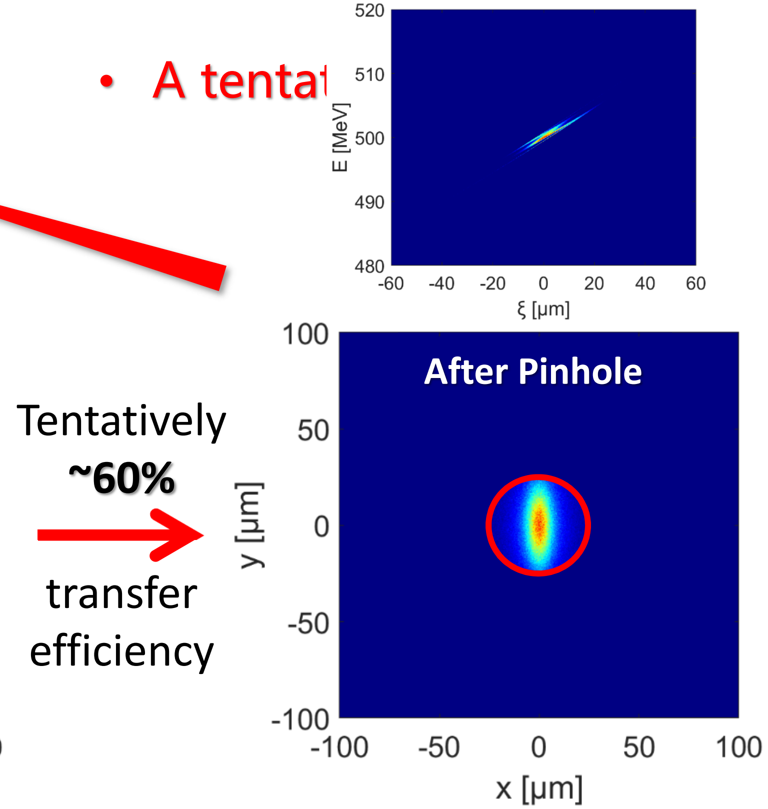
Tentatively **~60%** transfer efficiency



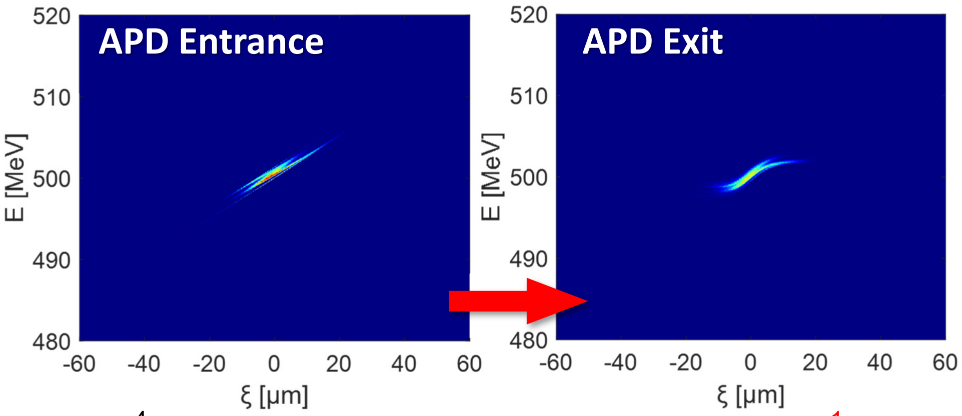
Beam Transfer Line Design (Pinhole)

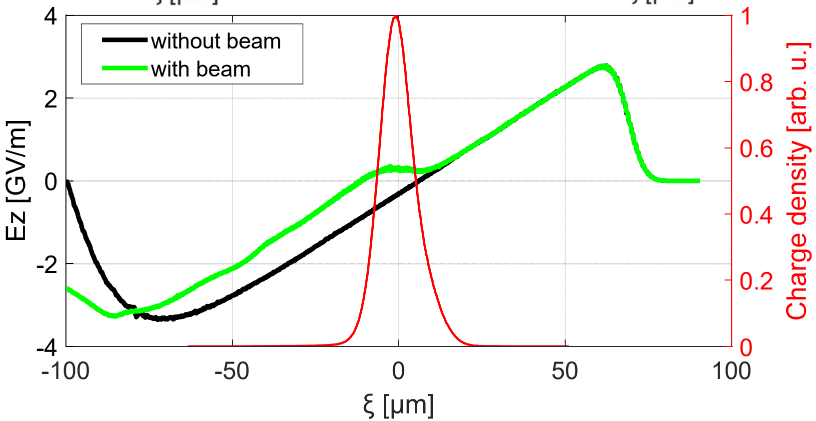


- A tentat



Active Plasma Dechirper Simulation (50 pC)

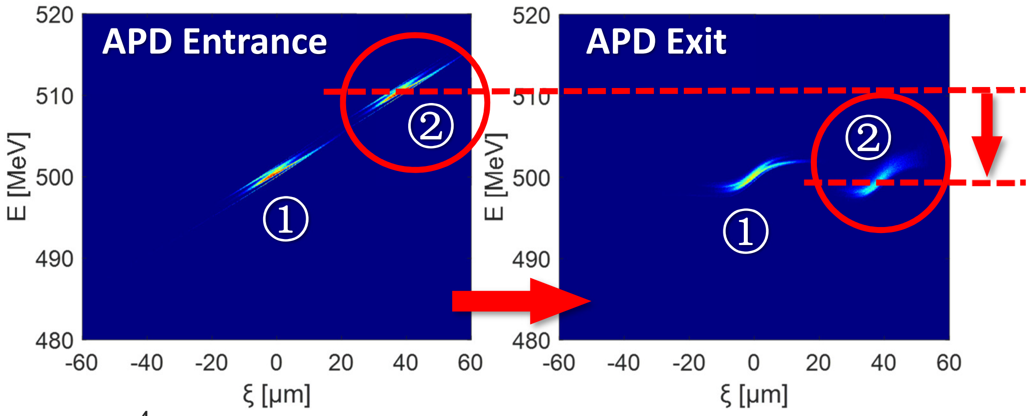


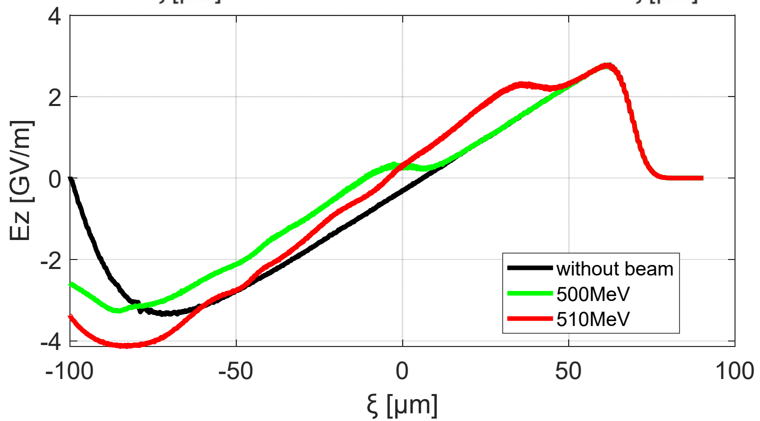


- Test the effectiveness for an electron bunch with central energy 500 MeV
- Beam loading in the active plasma dechirper plays a role.
  - The linear Ez provided by the APD was "flattened".

Designed Central Energy (MeV)	Central Energy Deviation (MeV)		Energy Spread	
	LPA exit	APD exit	LPA exit	APD exit
500	0.51	0.22	0.94%	0.24%

Active Plasma Dechirper Simulation (50 pC)

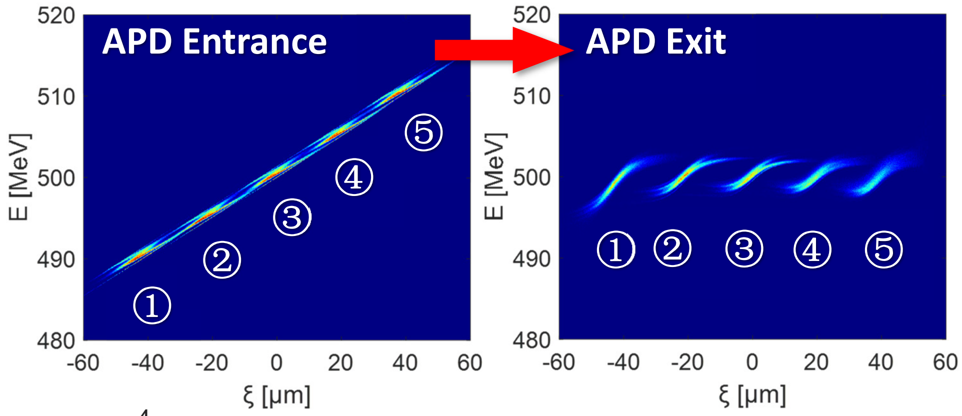


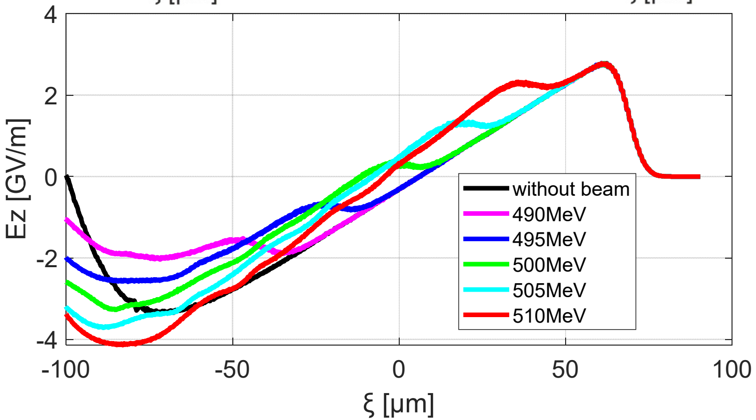


- Test the effectiveness for an electron bunch with central energy deviation
  - Energy deviation of the bunch ② was successfully reduced.

Designed Central Energy (MeV)	Central Energy Deviation (MeV)		Energy Spread	
	LPA exit	APD exit	LPA exit	APD exit
500	0.51	0.22	0.94%	0.24%
510	10.51	0.01	0.94%	0.36%

Active Plasma Dechirper Simulation (50 pC)

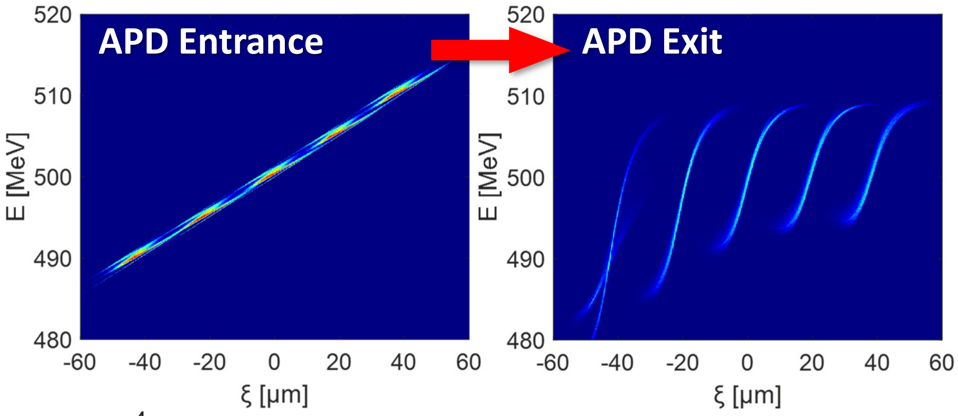


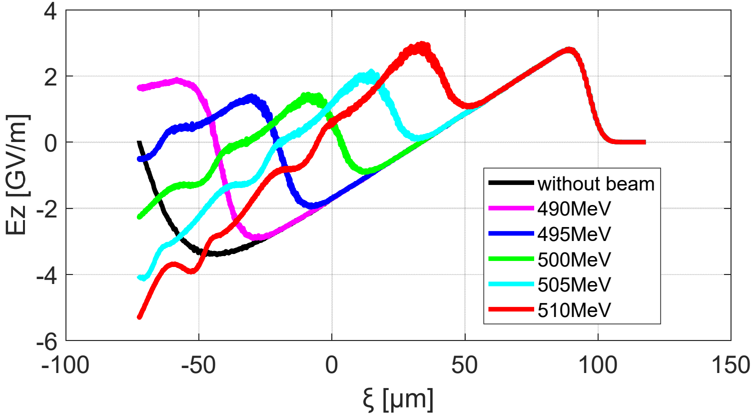


- Test the effectiveness for larger energy deviation
  - Assuming the central energy deviation ±1% and ±2%

Designed Central Energy (MeV)	Central Energy Deviation (MeV)		Energy Spread	
	LPA exit	APD exit	LPA exit	APD exit
490	-9.49	-0.68	0.94%	0.41%
495	-4.49	0.19	0.94%	0.28%
500	0.51	0.22	0.94%	0.24%
505	5.51	0.05	0.94%	0.24%
510	10.51	0.01	0.94%	0.36%

Active Plasma Dechirper Simulation (200 pC)

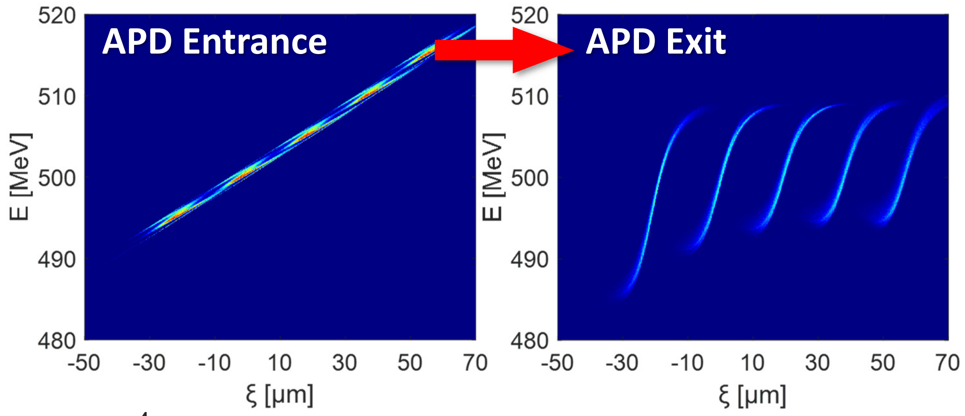




- Test the effectiveness for larger energy deviation
  - Assuming the central energy deviation ±1% and ±2%

Designed Central Energy (MeV)	Central Energy Deviation (MeV)		Energy Spread	
	LPA exit	APD exit	LPA exit	APD exit
490	-9.49	-8.50	0.94%	1.50%
495	-4.49	-3.49	0.94%	1.39%
500	0.51	-0.44	0.94%	1.07%
505	5.51	0.70	0.94%	0.94%
510	10.51	1.10	0.94%	0.90%

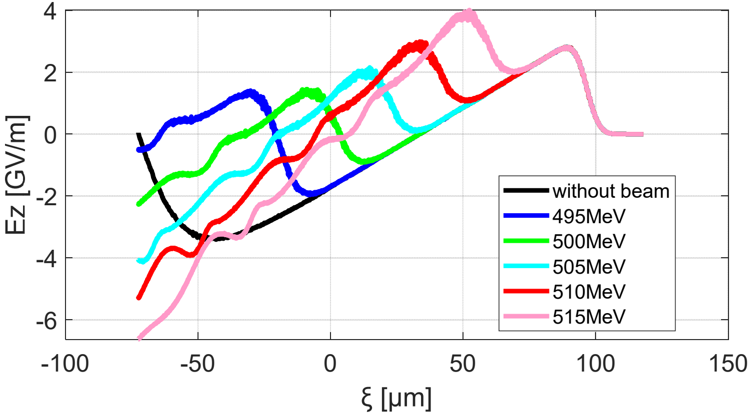
Active Plasma Dechirper Simulation (200 pC) --- slightly off energy



- 500±10 MeV -> 500+15 MeV / 500– 5 MeV

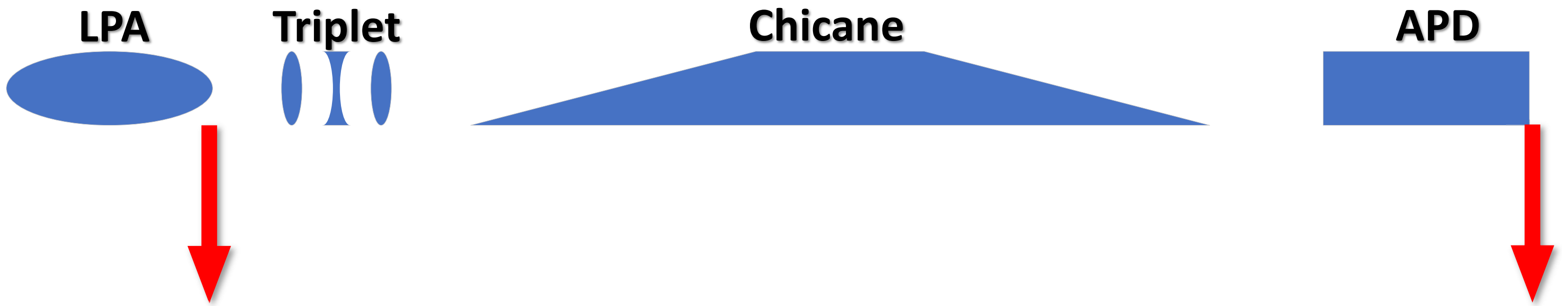
500+1.10 MeV
500–**8.50** MeV

500+1.10 MeV
500–**3.49** MeV



Designed Central Energy (MeV)	Central Energy Deviation (MeV)		Energy Spread	
	LPA exit	APD exit	LPA exit	APD exit
495	-4.49	-3.49	0.94%	1.39%
500	0.51	-0.44	0.94%	1.07%
505	5.51	0.70	0.94%	0.94%
510	10.51	1.10	0.94%	0.90%
515	15.51	1.08	0.94%	0.93%

Where We Are?



Energy	:	500 MeV
Energy Deviation	:	± 2%
Energy Spread	:	1%

50 pC →

Energy	:	500 MeV
Energy Deviation	:	– 0.14% ~ + 0.04%
Energy Spread	:	0.24% ~ 0.41%

- Preliminary study showed that the central energy deviation of a 50 pC bunch could be reduced from **± 2%** to the range **(– 0.14% , + 0.04%)**.

Where We Are?

Energy	:	500 MeV
Energy Deviation	:	± 2%
Energy Spread	:	1%

50 pC →

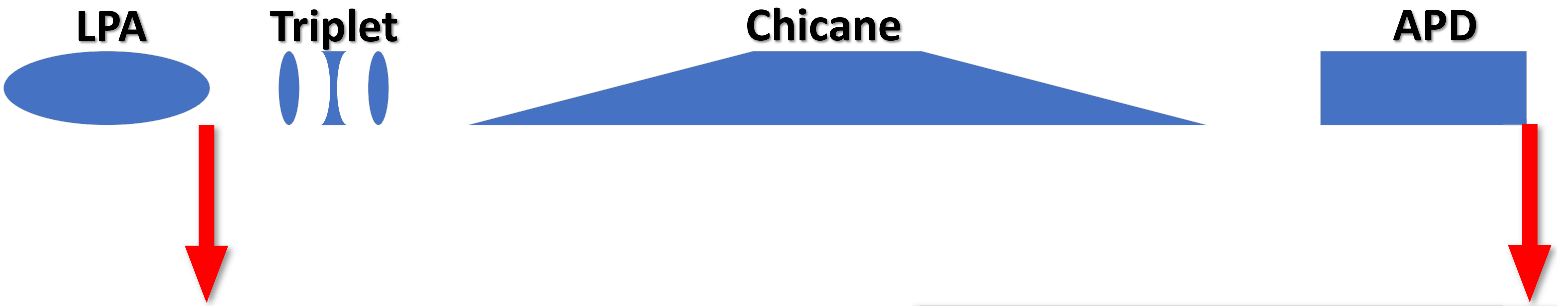
Energy	:	500 MeV
Energy Deviation	:	– 0.14% ~ + 0.04%
Energy Spread	:	0.24% ~ 0.41%

200 pC →

Energy	:	500 MeV
Energy Deviation	:	– 1.70% ~ + 0.22%
Energy Spread	:	0.90% ~ 1.50%

- However, the suppression of central energy deviation for a 200 pC bunch was not as good: reduced from **± 2%** to the range **(– 1.70% , + 0.22%)**.

Where We Are?



Energy	:	500 MeV
Energy Deviation	:	± 2%
Energy Spread	:	1%

→ **200 pC**

Energy	:	500 MeV
Energy Deviation	:	– 1.70% ~ + 0.22%
Energy Spread	:	0.90% ~ 1.50%

Energy	:	500 MeV
Energy Deviation	:	– 1% ~ + 3%
Energy Spread	:	1%

→ **200 pC**

Energy	:	500 MeV
Energy Deviation	:	– 0.70% ~ + 0.22%
Energy Spread	:	0.90% ~ 1.39%

- slightly off-energy operation of a 200 pC bunch could be helpful for the suppression of central energy deviation.

4. Summary and Outlook

Summary & Outlook

- Preliminary studies showed that the scheme (Chicane + APD) managed to reduce the central energy deviation and energy spread simultaneously for relatively low charge bunch (e.g. 50 pC).
- The achieved energy spread now is still not as good as the previous work using X-band cavity as the dechirper (S. A. Antipov et.al. Phys. Rev. Accel. Beams. 24.111301 (2021)). However, it seems acceptable for the application as an injector of booster synchrotrons. Further optimizations of the APD design may help control the energy spread better.
- We extended the study to higher charge situations, which was challenging due to heavier beam loading. Preliminary results showed that central energy deviation can be reduced even for a 200 pC bunch. We found that the slightly off-energy operation could be helpful for controlling the final central energy.
- Still a lot of work to do (chromaticity correction, improvement of beam transfer efficiency, beam loading suppression,……)

Thanks for your attention!