Suppression of microbunching instability by laser-modulated microbunching compression

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Introduction

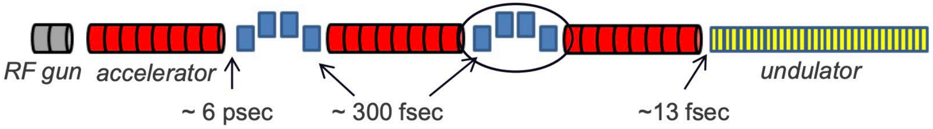
1. What are we going to study and why should it happen at ATF
2. Description of experiment and analytical estimates
3. Simulation of planned experiment
4. Hardware considerations
5. Conclusion

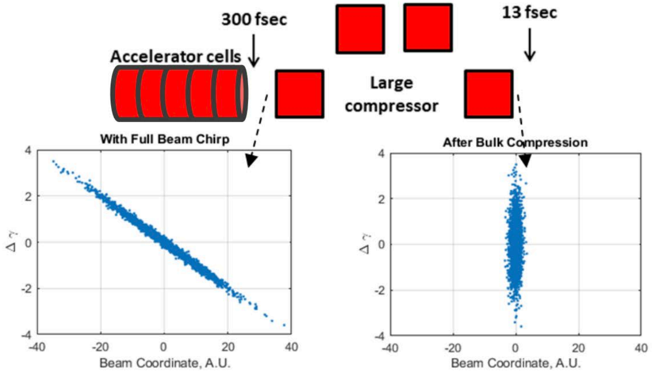
Reason for Experiment

Novel Accelerator Architecture for XFELs

Our proposed alternative XFEL architecture may have a major impact on the performance and energy reach of existing and proposed XFELs

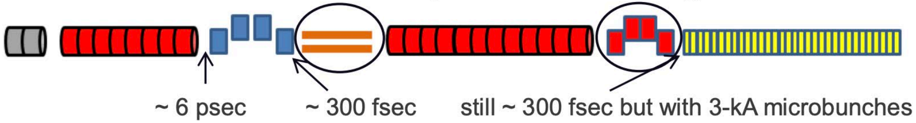
We would replace the second bunch compressor in a conventional design

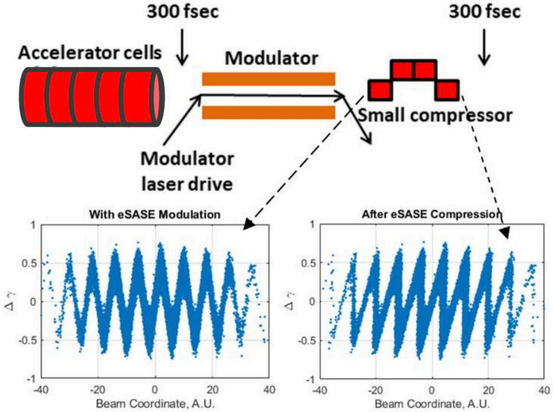




Compression of the entire bunch to the ~ 3 kA needed for lasing causes other problems – undulator resistive wall wake, microbunch instability, CSR enhancement

with a modulator/buncher that keeps an overall longer bunch





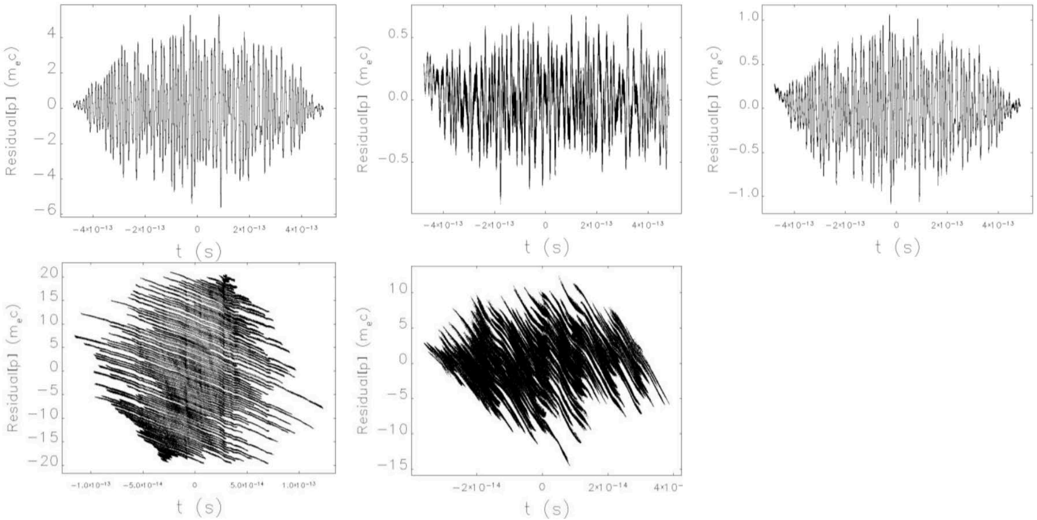
The other problems are reduced (or eliminated)with this new architecture

Problem being solved

eSASE architecture eliminates the MicroBunch Instability (MBI) which is recognized as the key limitation of existing XFELs

before BC2

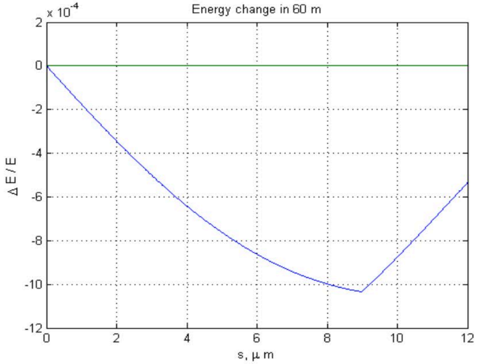
after BC2

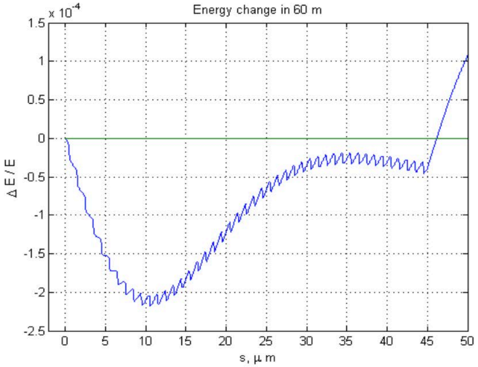


Cold beam **Laser-heated beam** **eSASE beam**

(these simulations are for 450:1 total compression ratio)

A microbunched beam eliminates the MBI growth mechanism





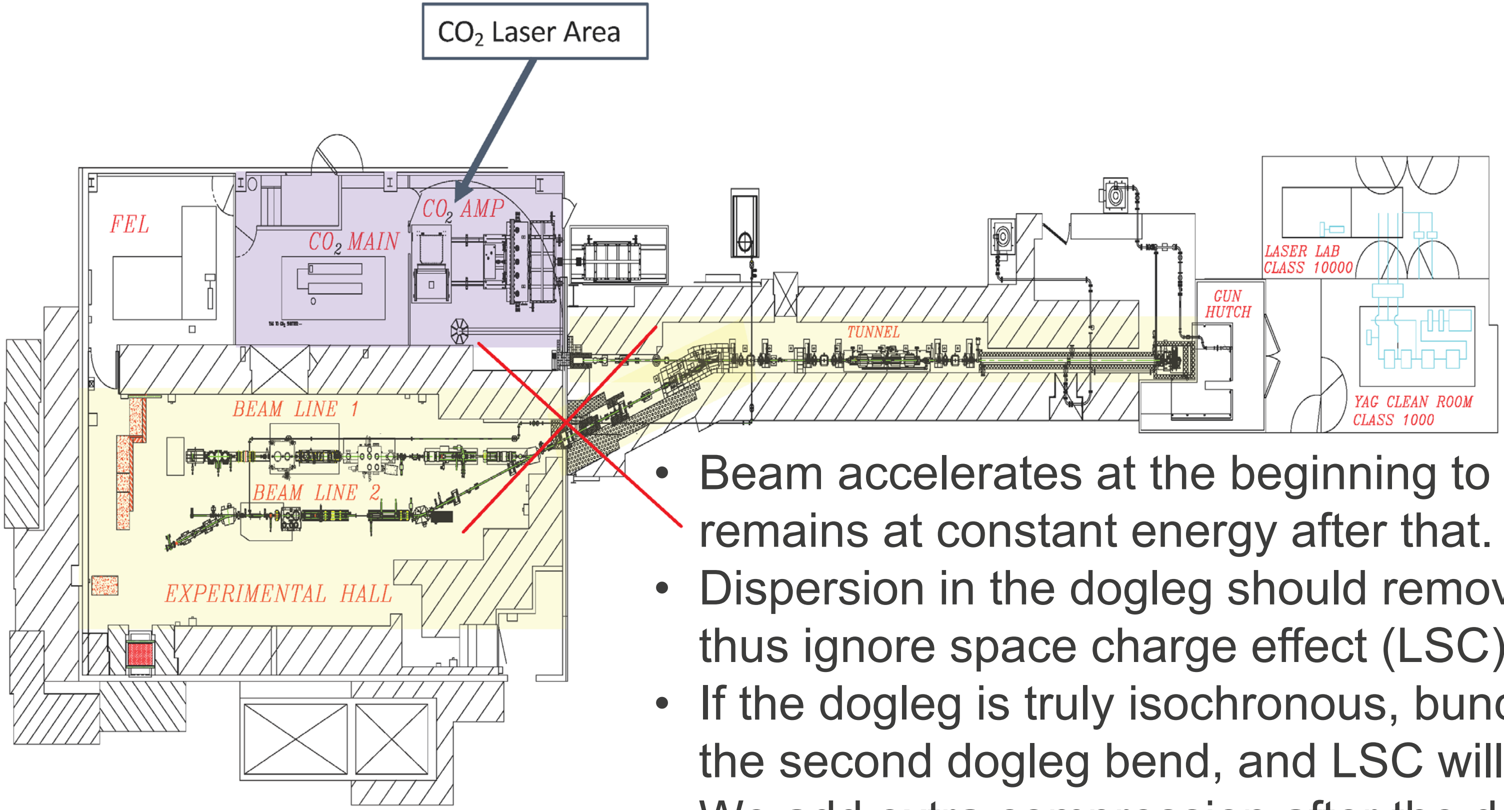
The magnitude of the URWW is also reduced by a factor of ~ 5, making it a non-issue

Why ATF is Ideal

- ATF has a co-located high brightness electron beam and laser.
- Beamline properties and 10-um laser are ideal for microbunching study.
- Previous experiments provide most of the hardware that we need:
  - The Rubicon experiment provides buncher and small chicane
  - T-cav provides a diagnostic to measure bunching and energy spread
  - Existing chicane can be coupled with a second chicane to enhance the microbunching instability.
- Novel eSASE-based XFEL architecture is under serious consideration by an international team led by LANL and UCLA, with potential high-impact on the LANL MaRIE XFEL and the UCLA compact XFEL designs.
- We are working with ATF staff to determine the best experimental configuration:
  - Year 1: Preliminary beamline studies (80 hours) to confirm we can excite the microbunch instability with a chicane on either side of the dogleg.
  - Year 2: Microbunch instability suppression demonstration with an eSASE configuration (160 hours).

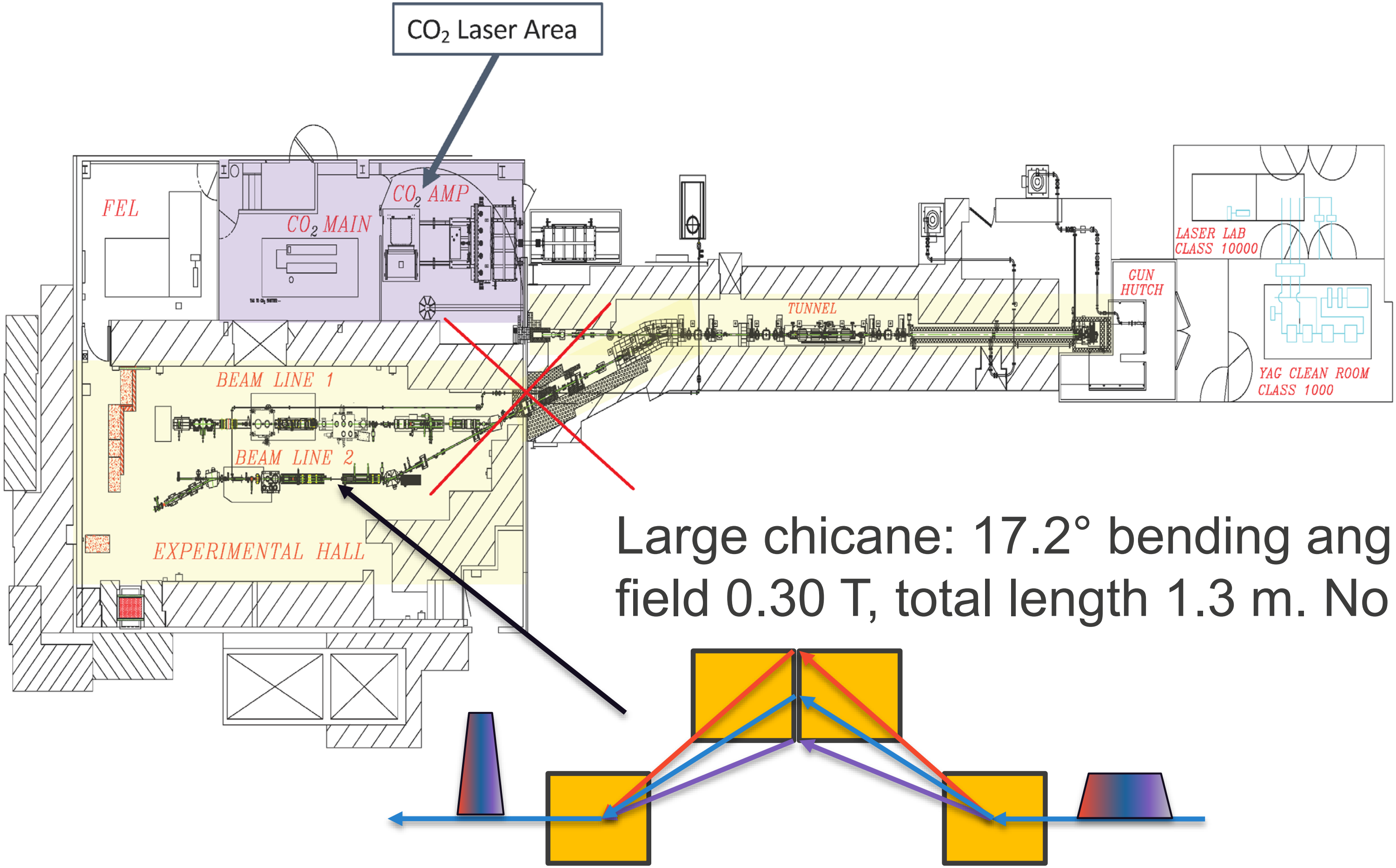
Experiment Description and Analytical Predictions

Novel compression scheme demonstration at ATF



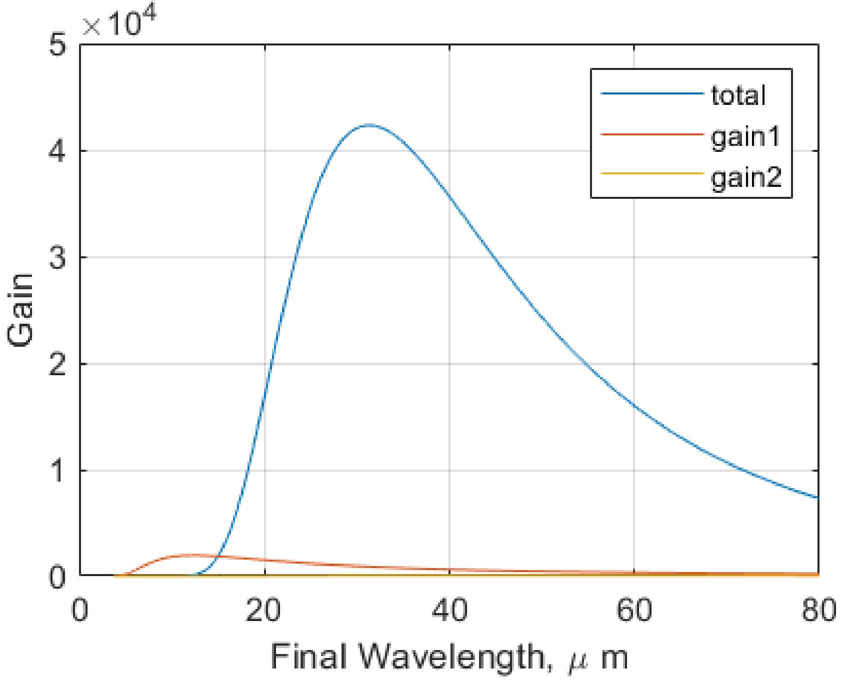
- Beam accelerates at the beginning to 60 MeV and then remains at constant energy after that.
- Dispersion in the dogleg should remove bunching, we thus ignore space charge effect (LSC) in that region.
- If the dogleg is truly isochronous, bunching will return at the second dogleg bend, and LSC will return.
- We add extra compression after the dogleg, in beam line 2. We will compare bulk compression vs LABC.

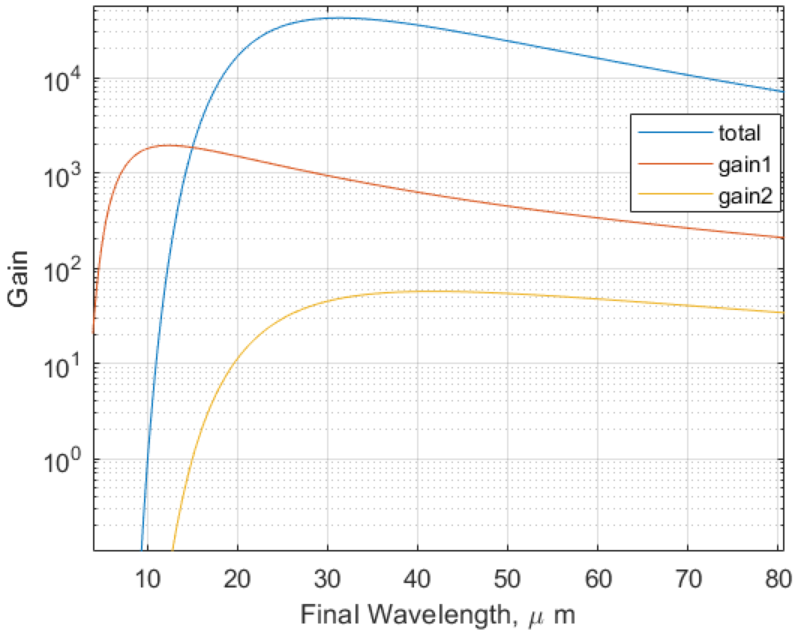
Experiment #1: Bulk compression



Large chicane: 17.2° bending angle, peak field 0.30 T, total length 1.3 m. No CO2 laser.

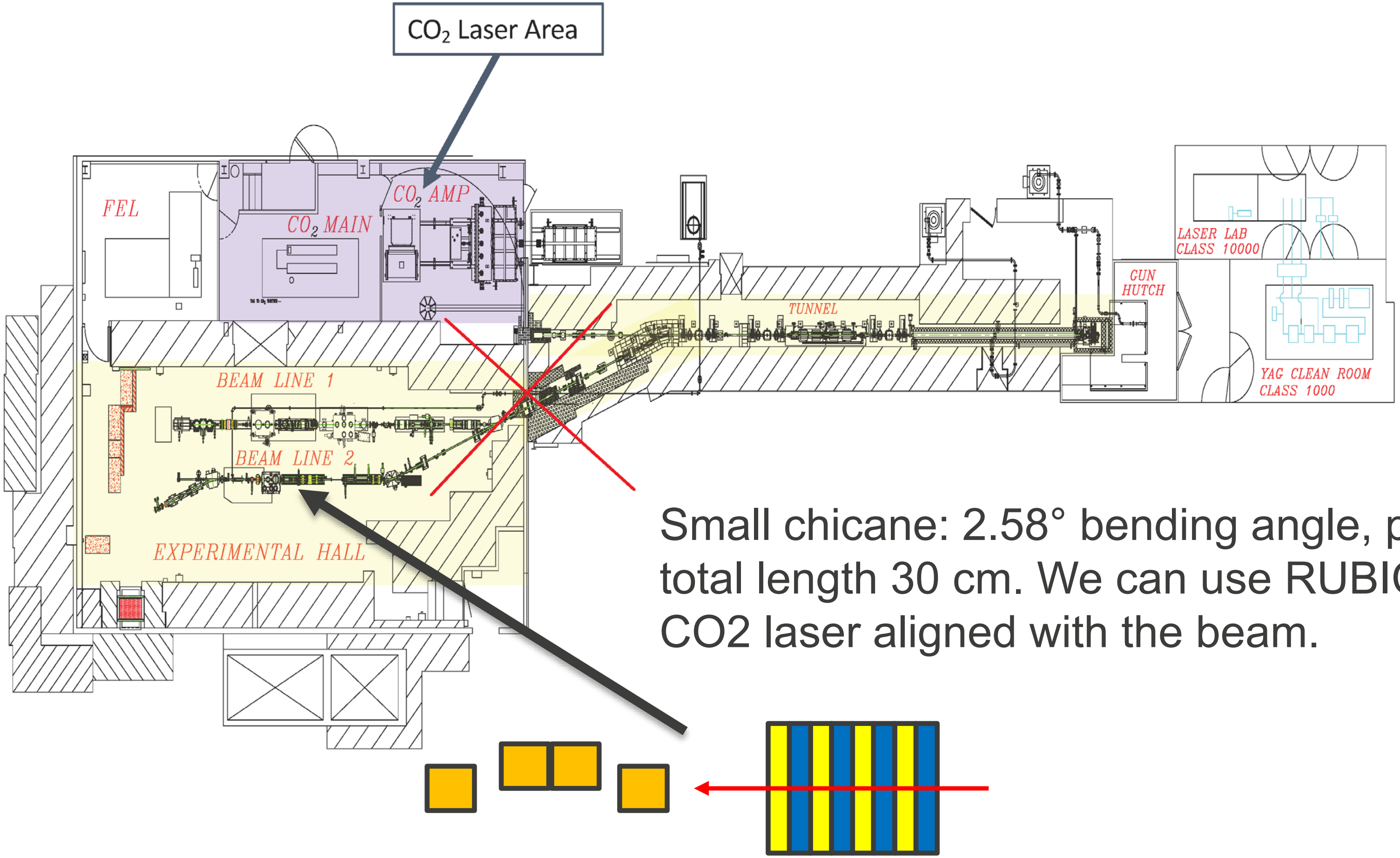
Microbunching instability Gain from bulk compression





Initial energy spread: 3.0 keV
High gain1 is needed to make detection possible.

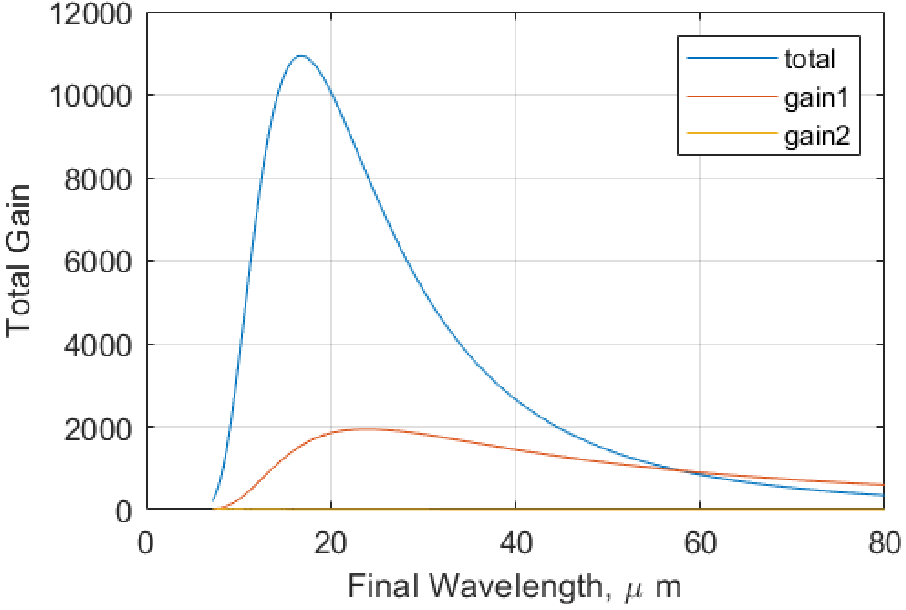
Experiment #2, Laser assisted bunch compression

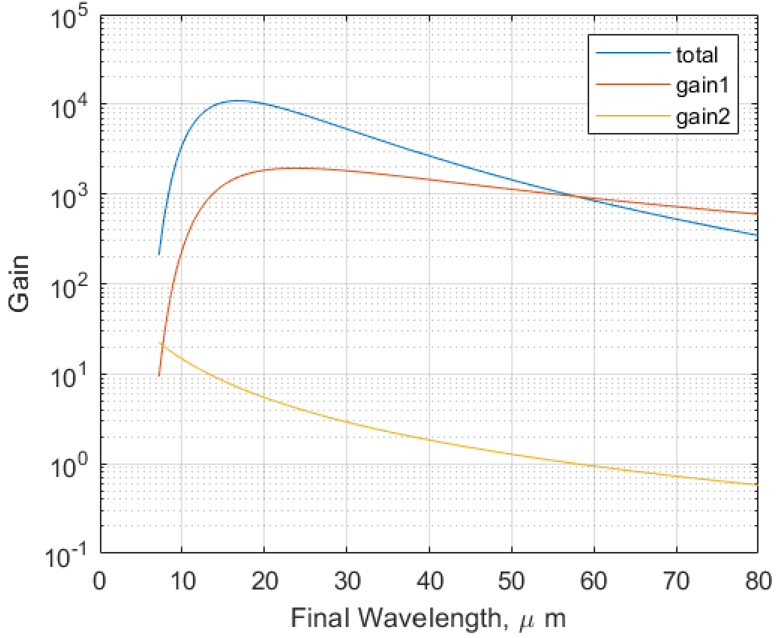


CO$_2$ Laser Area

Small chicane: 2.58° bending angle, peak field 0.18 T, total length 30 cm. We can use RUBICON 1st buncher. CO2 laser aligned with the beam.

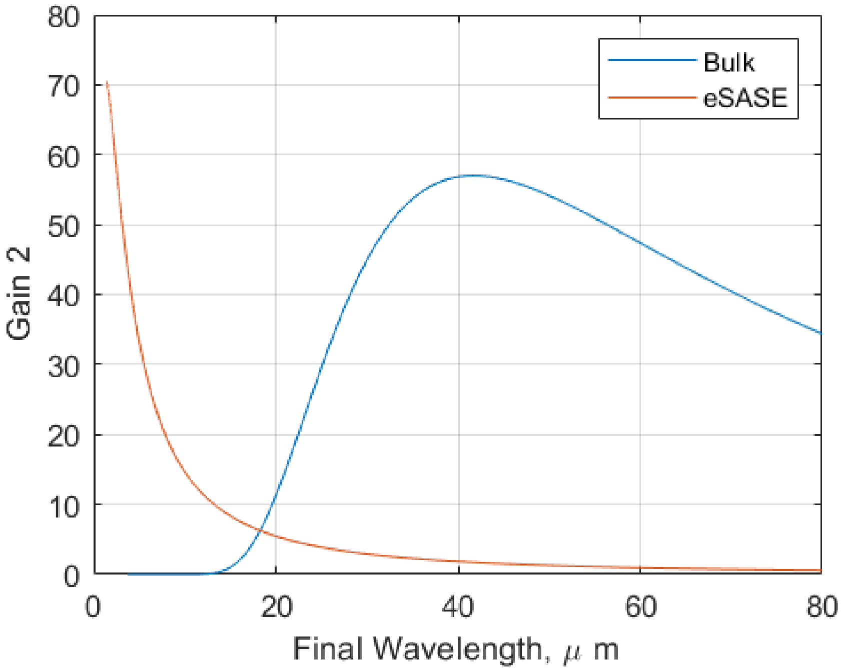
Microbunching instability Gain from LABC compression

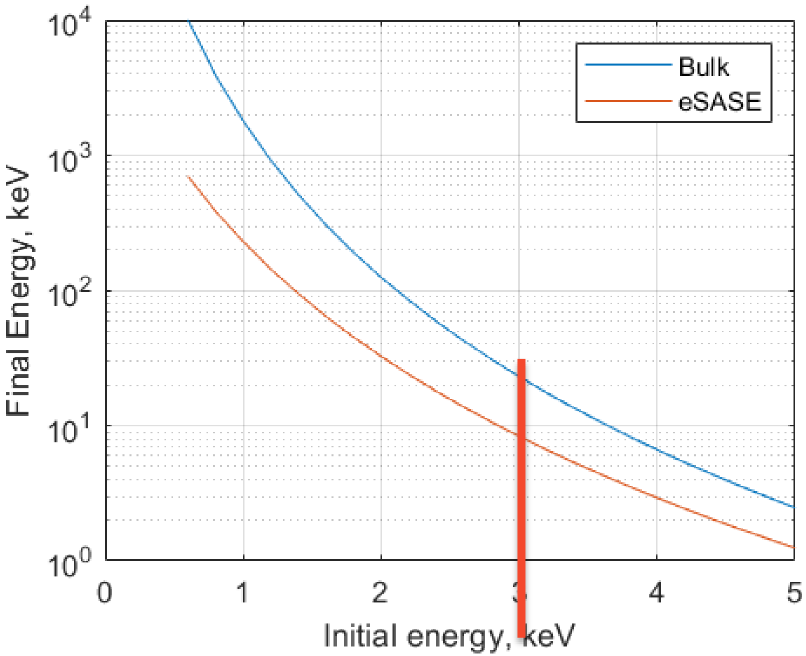




Initial energy spread: 3.0 keV
High gain1 is needed to make detection possible.

ATF experiment expectation



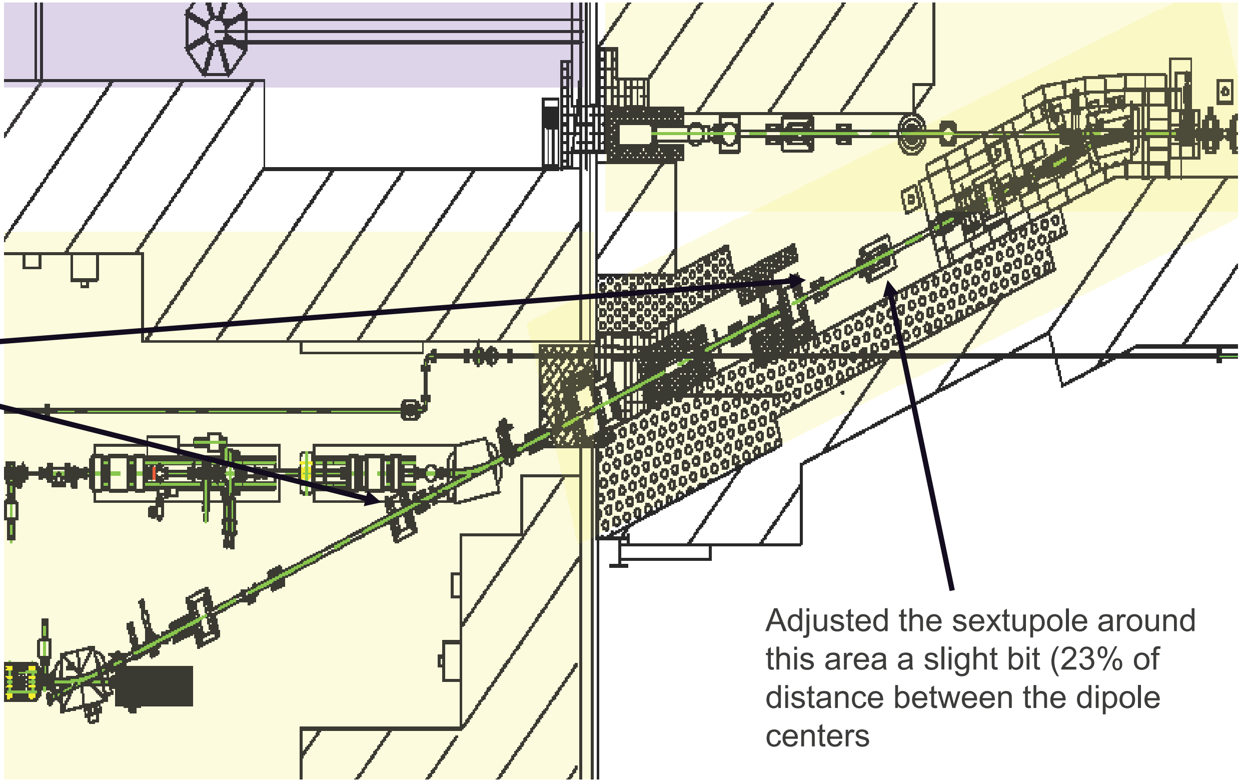


- Laser assisted bunch compression has significantly lower gain and energy spread from the microbunching instability.
- We should be able to measure this using x-band deflecting cavity at ATF. We hope to measure down to 10 um.

Simulation of Experiment

Dispersion in Dogleg

Dogleg is ~ isochronous but has significant higher order effects on the order of 0.02 mm/%^{2} and R15 and R25 terms that smear out ~ 30 um variations

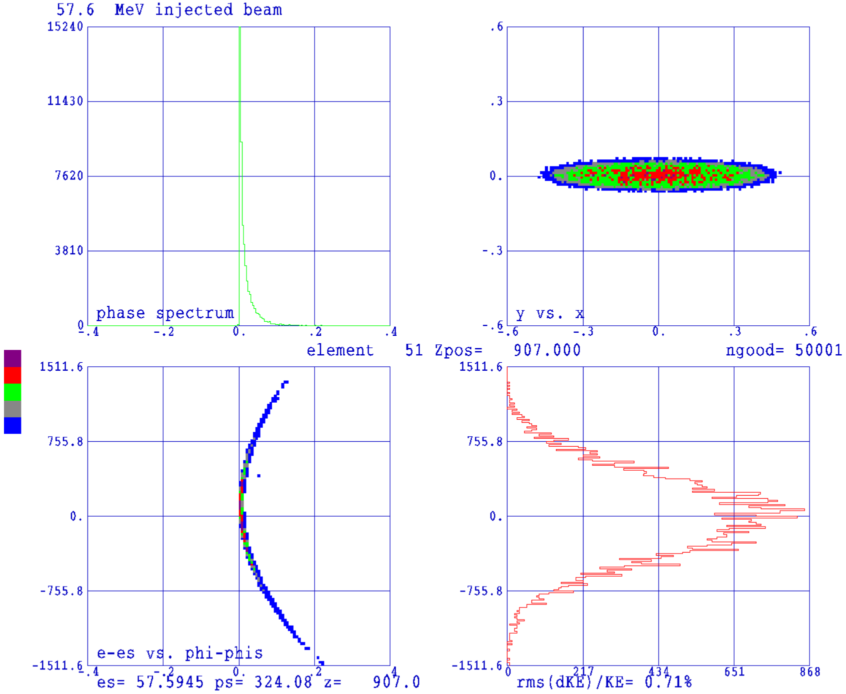


Symmetrically slightly adjusted a quad at 31% and one at at 69% of the distance along the dogleg

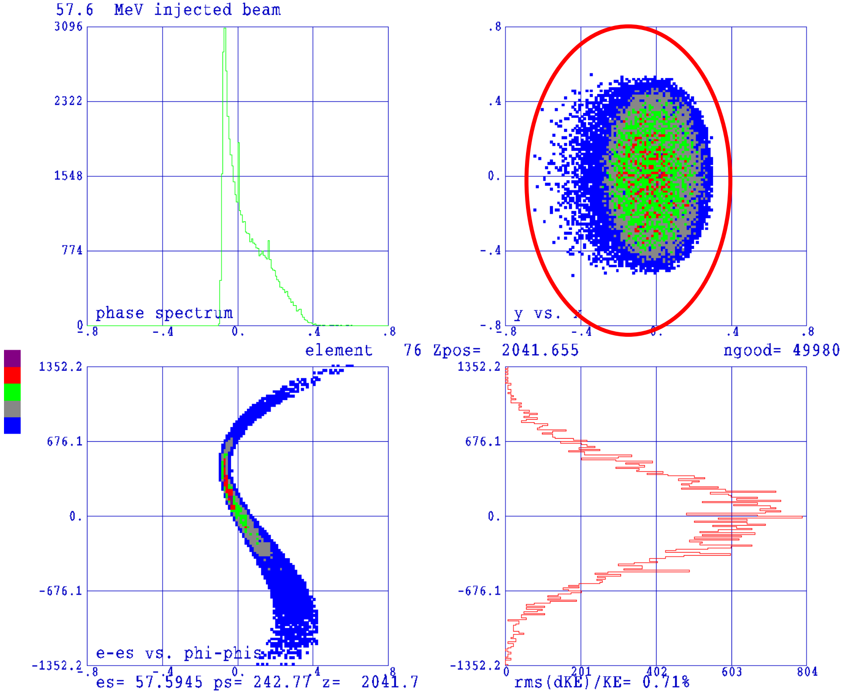
Adjusted the sextupole around this area a slight bit (23% of distance between the dipole centers

Dogleg continued

After chicane



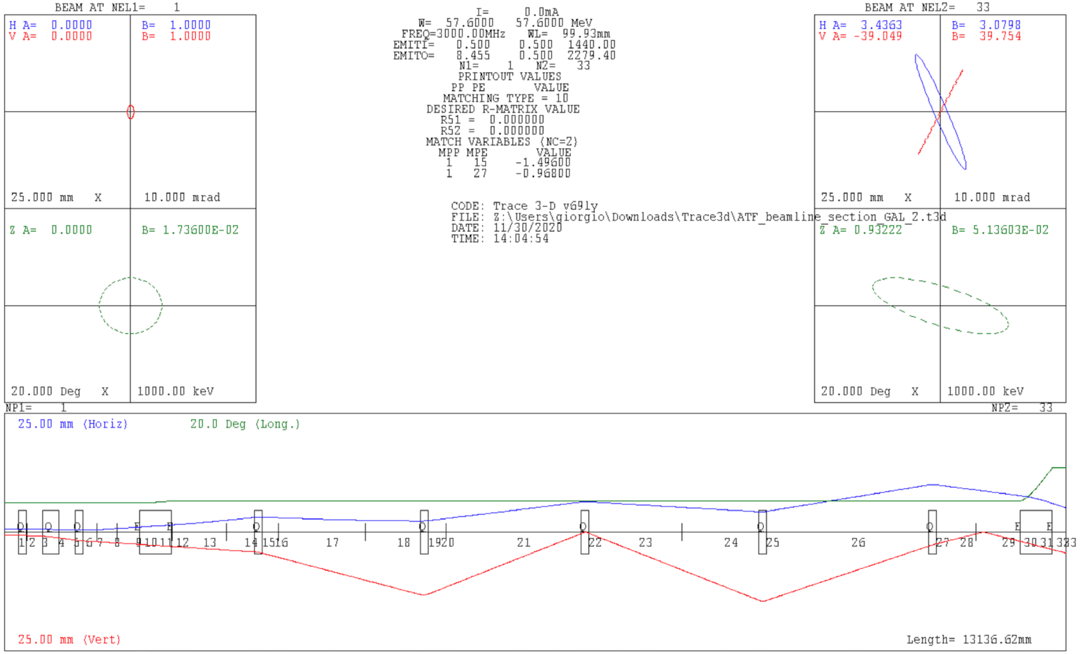
Exit of dogleg



Required minor tuning of the dogleg (+2.2 G/cm on the two quads and 11 G/cm^2 on the sextupole) and entrance focusing (-90 G/cm)

Modelling F1 section of the ATF beamline in Trace3D

- Using Trace3D to eliminate R51 and R52 from dogleg.
- R51 and R52 are not 0 yet, which would suppress microbunching instability in BC1 that we need in order to detect microbunching instability in BC2.



```
          I=      0.0mA
    W=  57.6000   57.6000 MeV
  FREQ=3000.00MHz   WL=  99.93mm
 EMITI=   0.500    0.500  1440.00
 EMITO=   8.455    0.500  2279.40
           N1=    1   N2=   33
          PRINTOUT VALUES
         PP PE        VALUE
       MATCHING TYPE = 10
     DESIRED R-MATRIX VALUE
        R51 =  0.000000
        R52 =  0.000000
     MATCH VARIABLES (NC=2)
       MPP MPE         VALUE
        1   15     -1.49600
        1   27     -0.96800

          CODE: Trace 3-D v69ly
          FILE: Z:\Users\giorgio\Downloads\Trace3d\ATF_beamline_section_GAL_2.t3d
          DATE: 11/30/2020
          TIME: 14:04:54
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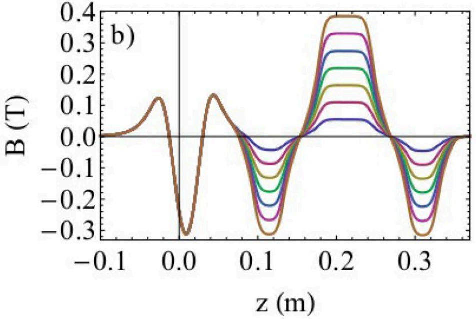
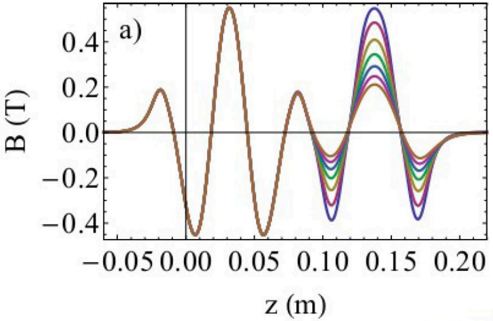
Hardware Considerations

Available equipment at ATF - bunchers



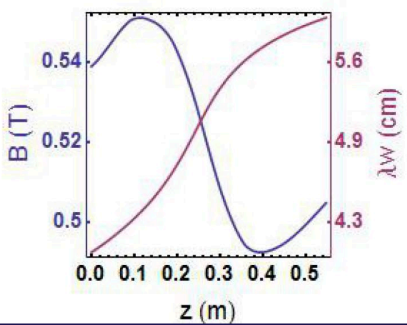
1^{st} buncher

- 7 cm - half period – planar undulator
- electro-magnetic chicane
  - R56 0-900 um



2^{nd} buncher

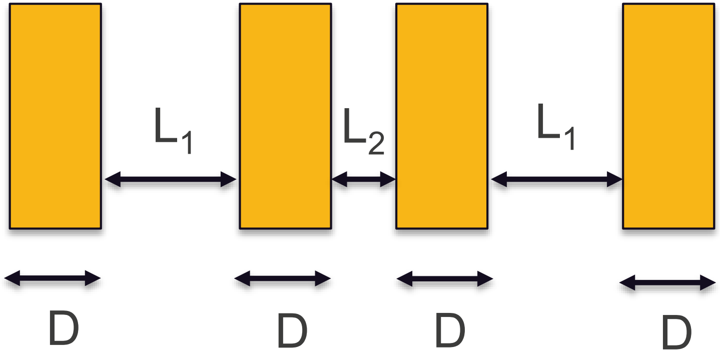
- 5 cm - 1 period – planar undulator
- variable gap permanent magnet chicane
  - R56 40-90 um



Rubicon undulator

- 4-6 cm period – 11 period - helical undulator
- gap tapered
- resonant phase: -π/4
- resonant energy: 52- 82 MeV

Chicanes for bulk and eSASE experiment



Large chicane for bulk compression:

- 17.2° bending angle
- D = 20 cm
- L1 = 10 cm
- 0.3 Tesla B-field
- Total Length = 1.3 meters

Small chicane for eSASE compression:

- 2.58° bending angle
- D = 5 cm
- L1 = 5 cm
- 0.18 Tesla B-field
- Total Length = 30 cm

Conclusion

- We believe that if the novel eSASE scheme is used to eliminate the need for a second large bunch compressor, it can lead to more affordable and lower risk XFELs.
- The eSASE concept is predicted to eliminate or reduce the need for a laser heater to suppress the microbunching instability.
- ATF, with its beamline, powerful CO2 laser and undulator, is uniquely positioned to study the use of eSASE to suppress the microbuncing instability.
- We are designing a preliminary experiment at ATF to do this study.

Special Slides

Electron Beam Requirements

Parameter	Units	Typical Values	Comments	Requested Values
Beam Energy	MeV	50-65	*Full range is ~15-75 MeV with highest beam quality at nominal values*	*60*
Bunch Charge	nC	0.1-2.0	*Bunch length & emittance vary with charge*	*0.5*
Compression	fs	Down to 100 fs (up to 1 kA peak current)	*A magnetic bunch compressor available to compress bunch down to ~100 fs. Beam quality is variable depending on charge and amount of compression required.* *NOTE: Further compression options are being developed to provide bunch lengths down to the ~10 fs level*	*500*
Transverse size at IP (σ)	μm	30 – 100 (dependent on IP position)	*It is possible to achieve transverse sizes below 10 um with special permanent magnet optics.*	*~50*
Normalized Emittance	μm	1 (at 0.3 nC)	*Variable with bunch charge*	*1 or min @ 0.5 nC*
Rep. Rate (Hz)	Hz	1.5	*3 Hz also available if needed*	*1.5*
Trains mode	---	Single bunch	*Multi-bunch mode available. Trains of 24 or 48 ns spaced bunches.*	*Single bunch*

CO2 Laser Requirements

Configuration	Parameter	Units	Typical Values	Comments	Requested Values
CO_2 Regenerative Amplifier Beam	Wavelength	µm	9.2	*Wavelength determined by mixed isotope gain media*	*9.2*
	Peak Power	GW	~3		*3*
	Pulse Mode	---	Single		*Single*
	Pulse Length	ps	2		*2*
	Pulse Energy	mJ	6		*1*
	M^2	---	~1.5		*1.5*
	Repetition Rate	Hz	1.5	*3 Hz also available if needed*	*1.5*
	Polarization	---	Linear	*Circular polarization available at slightly reduced power*	*Linear*
CO_2 CPA Beam	Wavelength	µm	9.2	*Wavelength determined by mixed isotope gain media*	
Note that delivery of full power pulses to the Experimental Hall is presently limited to Beamline #1 only.	Peak Power	TW	2	*~5 TW operation is planned for FY21 (requires further in-vacuum transport upgrade). A 3-year development effort to achieve >10 TW and deliver to users is in progress.*	
	Pulse Mode	---	Single		
	Pulse Length	ps	2		
	Pulse Energy	J	~5	*Maximum pulse energies of >10 J will become available in FY20*	
	M^2	---	~2		
	Repetition Rate	Hz	0.05		
	Polarization		Linear	*Adjustable linear polarization along with circular polarization will become available in FY20*	

Special Equipment Requirements and Hazards

- Electron Beam
  - We will need to use the transverse deflecting cavity. In addition, we will use one of the bunchers from the Rubicon experiment. We will use an additional chicane in the experimental hall, which will be provided by us. We may need to tune magnets inside the dogleg to eliminate dispersion.
- CO_2 Laser
  - The laser will need to interact with the electron beam inside the Rubicon buncher
- Ti:Sapphire and Nd:YAG Lasers
  - None
- Hazards & Special Installation Requirements
  - Installing new chicane
  - Tuning magnets in dogleg
  - High magnetic fields of undulator and chicane

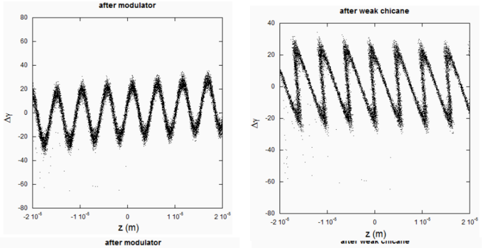
Problem being solved

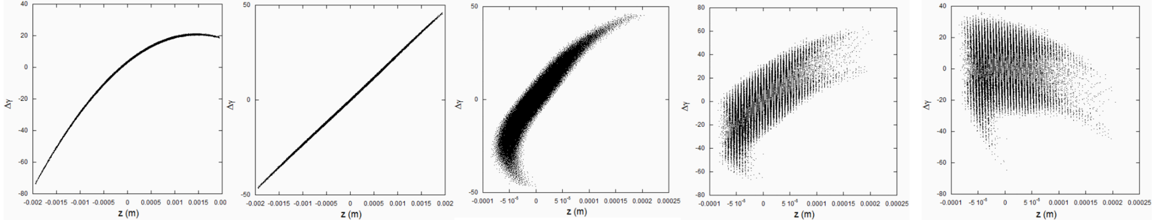
Illustrative simulations and simple scalings indicate this architecture may have a very significant impact, especially *reducing the risk of marginal designs* and *extending the range* of existing designs/XFELs

830 MeV before linearization

765 MeV after linearization

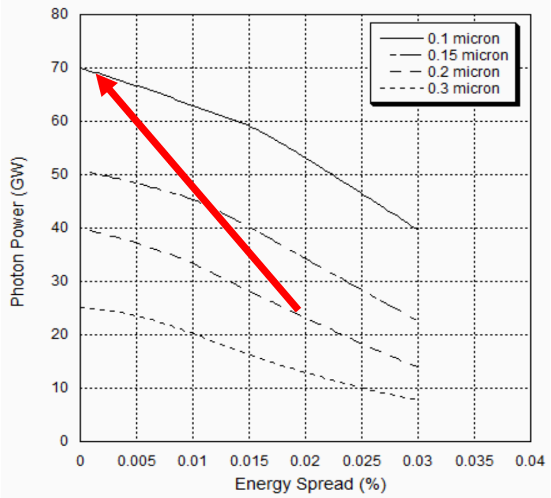
After bunch compressor





After small chicane buncher

After modulator



For MaRIE-type parameters:

MBI – reduce energy spread ~ 10

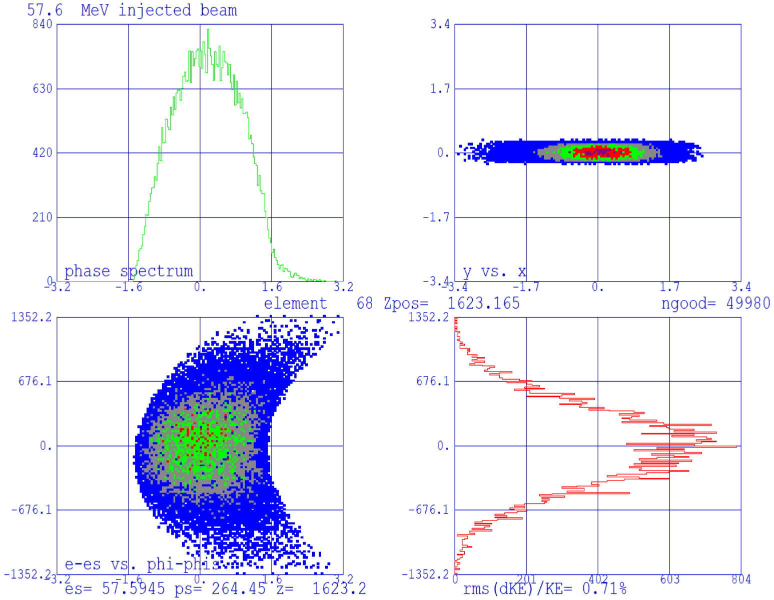
CSR – reduce emittance ~ 2

URWW – double X-ray flux

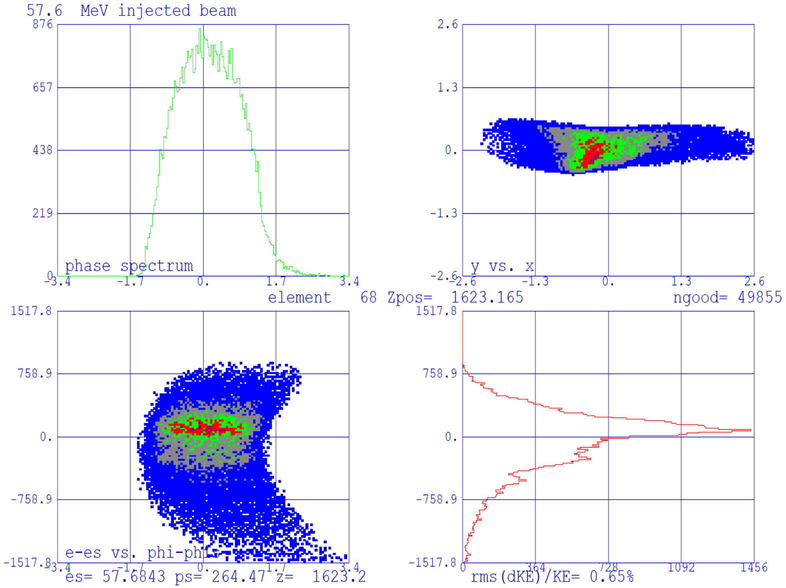
Net: 5x more flux

Transverse Space Charge

Parmela, no space charge



Parmela, with space charge



- Looking at end of section F1, see little difference from Parmela simulations with or without space charge.
- Because of this, we are using Elegant for experiment modeling, which includes CSR.

Experiment #1: Bulk compression params

Parameter	Value	Description
R56_1	88 mm	R56 of first chicane
R56_2	40 mm	R56 of second chicane
C1	4.33	Compression in first chicane
C2	1.95	Compression in second chicane
Emax	60.002 MeV	On crest acceleration
f	1.2 GHz	Frequency of RF
phi	-0.155 degrees	Phase of acceleration
Laccel	6.906 m	Length of accelerator
L1	4.57 m	Distance between accel. and BC1
L2	6.845 m	Distance between accel. And BC2
L3	5.881 m	Distance between BC2 and diagnostics
Iin	39.9 Amps	Input peak current
Qbunch	500 pC	Bunch charge
zrms	1.5 mm	Input bunch RMS size
Sig_r	100 um	Beam radial size

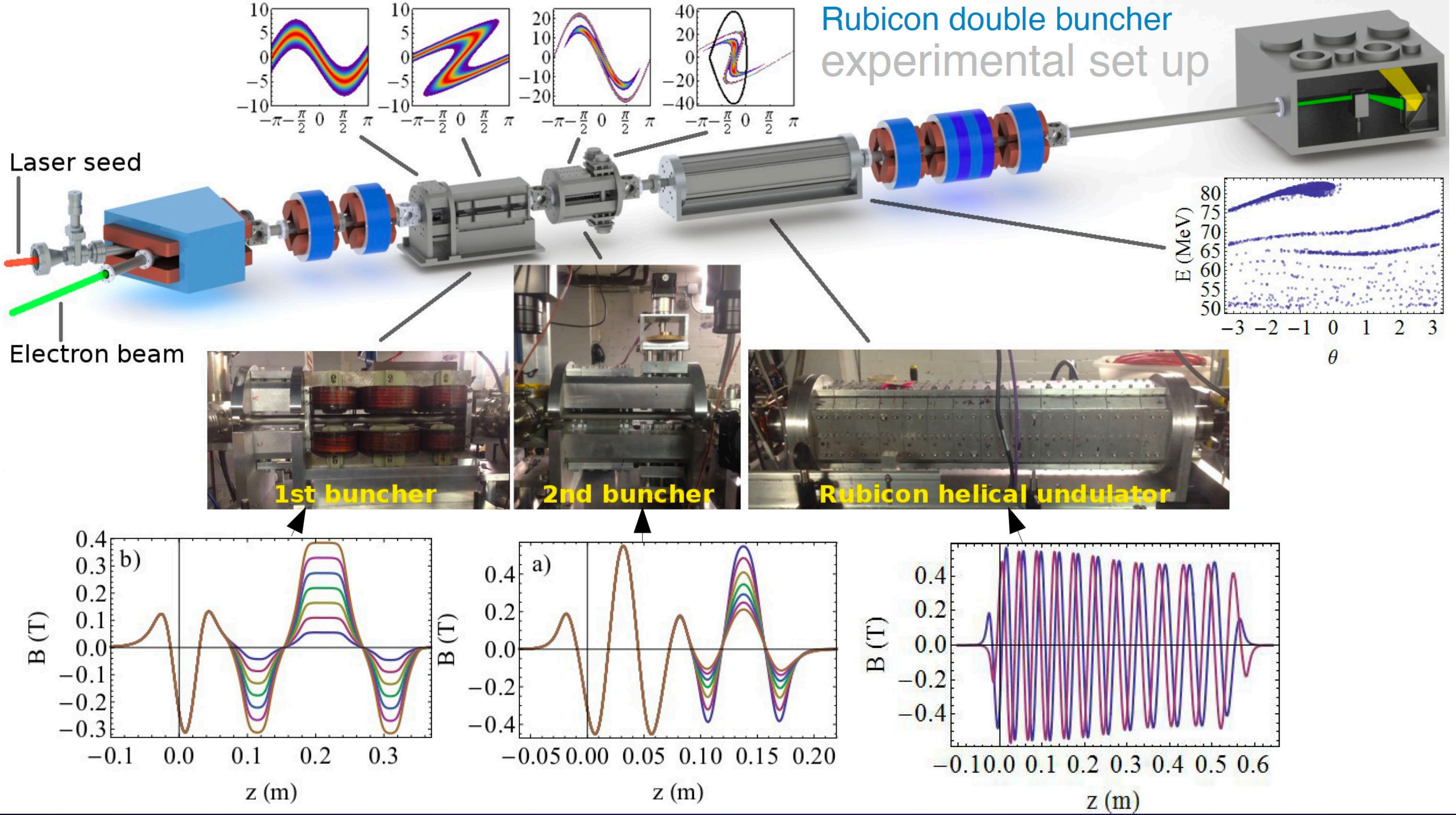
Experiment #2, Laser assisted bunch compression

Parameter	Value	Description
A	12	Modulation amplitude normalized to energy spread
B	0.06	R56 normalized to the laser wavelength
Laser Wavelength	10 um	CO2 laser
K und	1	LANL Navy FEL undulator param
L und	0.5	Non tapered part of LANL Navy FEL undulator, need to check this
Lam_und	2.5	Cm
Theta_resonant	26.3 mRad	Angle for resonant interaction is too big!
LABC compression ratio	6	approximate

Experiment #2, Laser assisted bunch compression

Parameter	Value	Description
R56_1	88 mm	R56 of first chicane
R56_2	331 um	R56 of second chicane
C1	4.33	Compression in first chicane
C2	1.01	Bulk compression in 2nd chicane
Emax	60.002 MeV	On crest acceleration
f	1.2 GHz	Frequency of RF
phi	-0.155 degrees	Phase of acceleration
Laccel	6.906 m	Length of accelerator
L1	4.57 m	Distance between accel. and BC1
L2	6.845 m	Distance between accel. And BC2
L3	5.881 m	Distance between BC2 and diagnostics
Iin	39.9 Amps	Input peak current
Qbunch	500 pC	Bunch charge
zrms	1.5 mm	Input bunch RMS size
Sig_r	100 um	Beam radial size

Available equipment at ATF - beamline



Rubicon double buncher experimental set up