The EEX-enabled microbunching experiment at the Argonne Wakefield Accelerator

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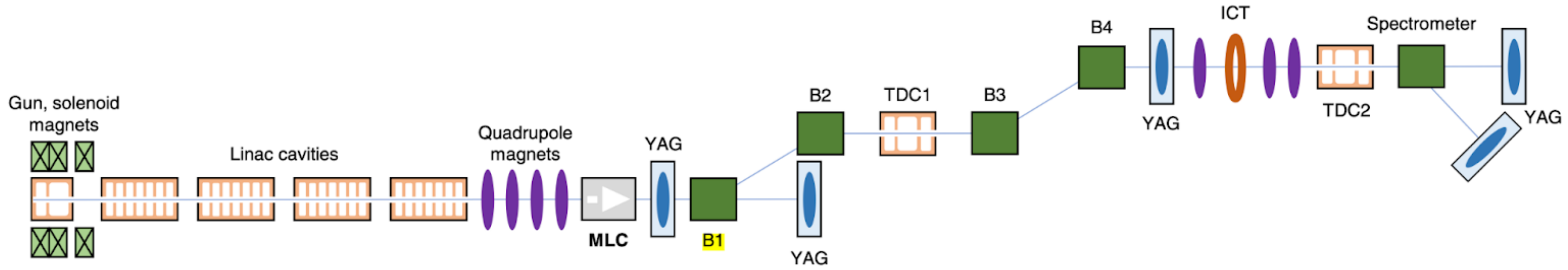
For UCLA-NIU-ANL-LANL-SLAC collaboration

AAC 2026 – July 30, 2026

Motivation

- The emittance exchange (EEX) process shows great promise for longitudinal beam shaping
  - Applications in wakefield acceleration
  - Basis of new types of coherent light source



AWA drive linac and EEX beamline (not to scale), adapted from [18] to include the MLC. There are six linac cavities at the AWA, but two cavities were not used in this experimental demonstration.

- **Coherent soft X-rays** obtained by converting transverse modulations to longitudinal?
  - Many unexplored physical effects – open field for investigation

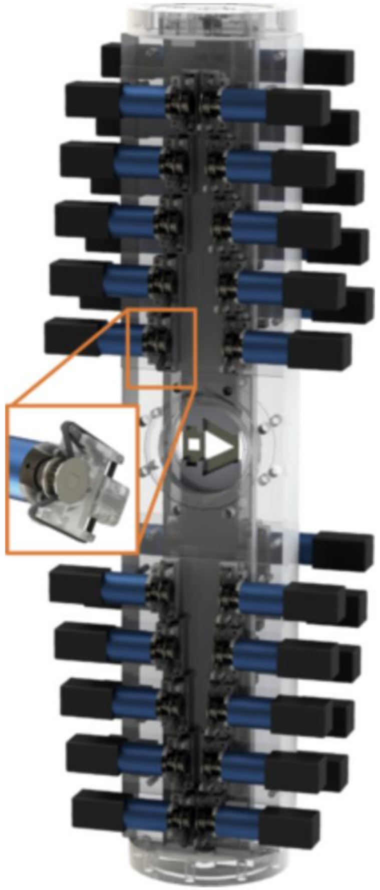
AAC application: beam shaping for wakefield accelerators

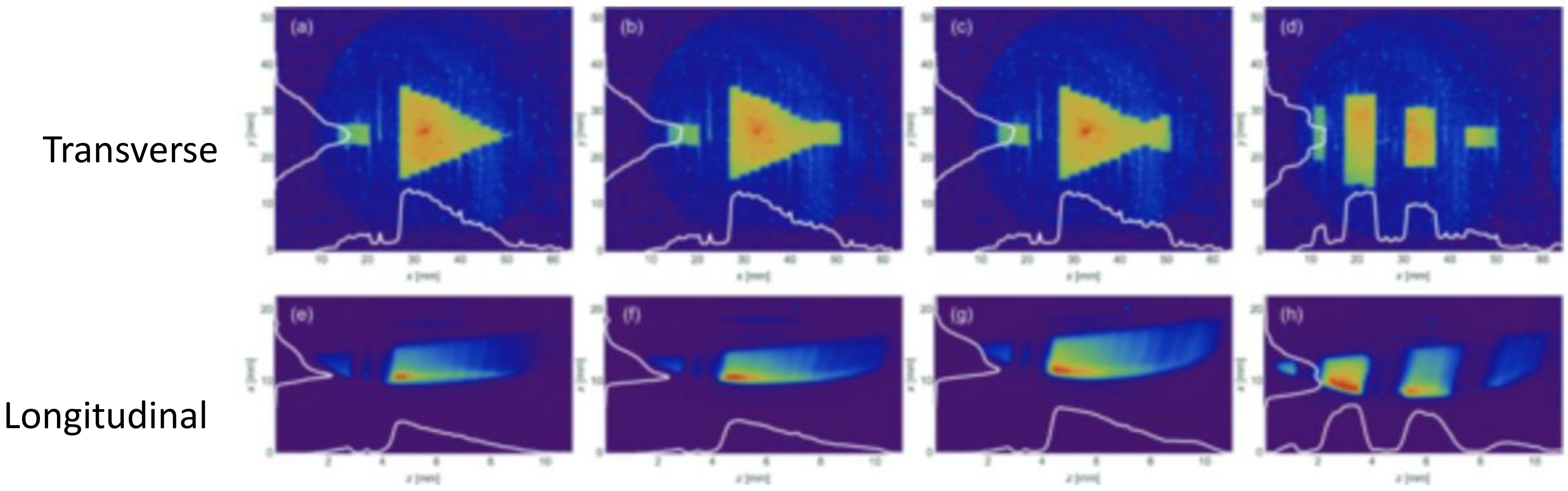
- High transformer ratio PWFA and DWA demonstrated

R. Roussel, et al., Phys. Rev. Lett. **124**, 044802 (2020)

- Recent work on multi-leaf collimator to refine process (ML emphasis)

N. Majernik, et al., Phys. Rev. Accel. Beams **26**, 022801 (2023)





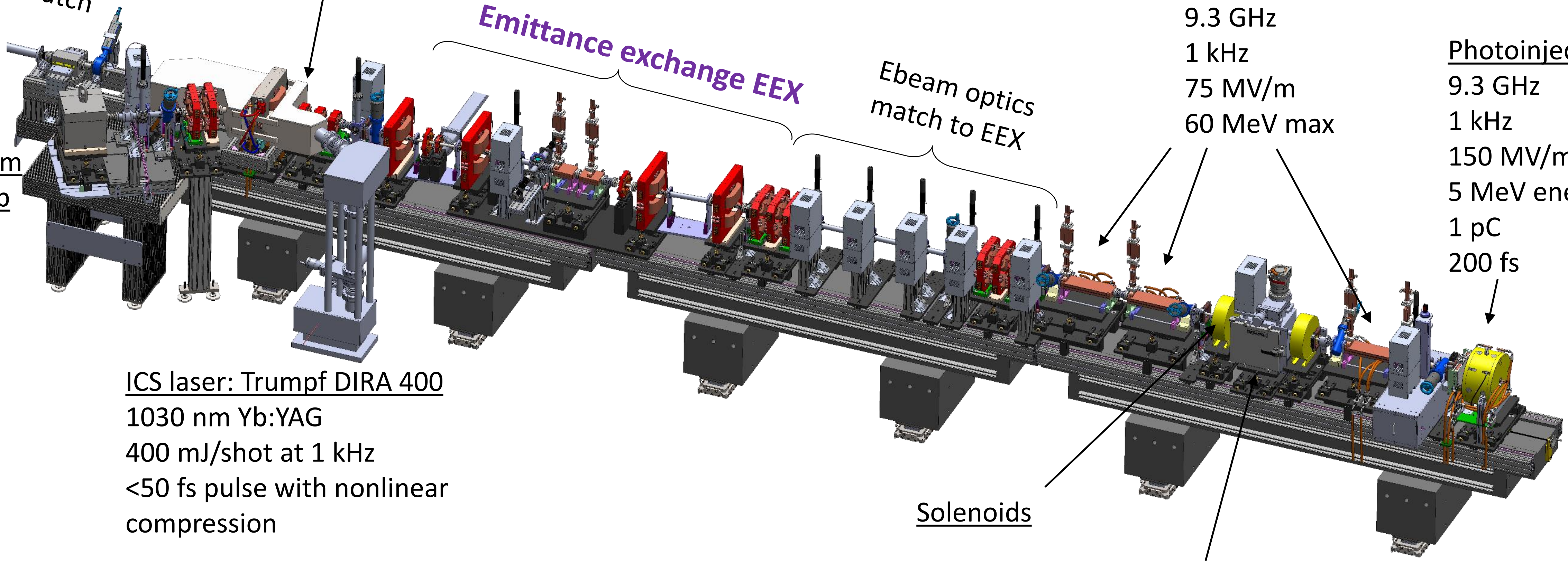
Power of collimation + EEX methods is demonstrated

Note residual correlations

How does EEX work?

- Step 1. Momentum dispersion in x (and t)
- Step 2. *Dipole mode cavity* for converting t to x'. Note that Panofsky-Wenzel theorem indicates x-dependent acceleration, giving correlated ΔE across the beam
- Step 3. Remove the correlation between the x and ΔE exploiting the x $x(t)$ correlation using a *fundamental mode* cavity. Small voltage
- Step 4. Remove momentum dispersion with dogleg
- NB: Doglegs must be sextupole corrected
- NB: Transformation done correctly *exchanges* horizontal and longitudinal emittance. Longitudinal is quite large!

Emerging application: ASU CXFEL employs EEX



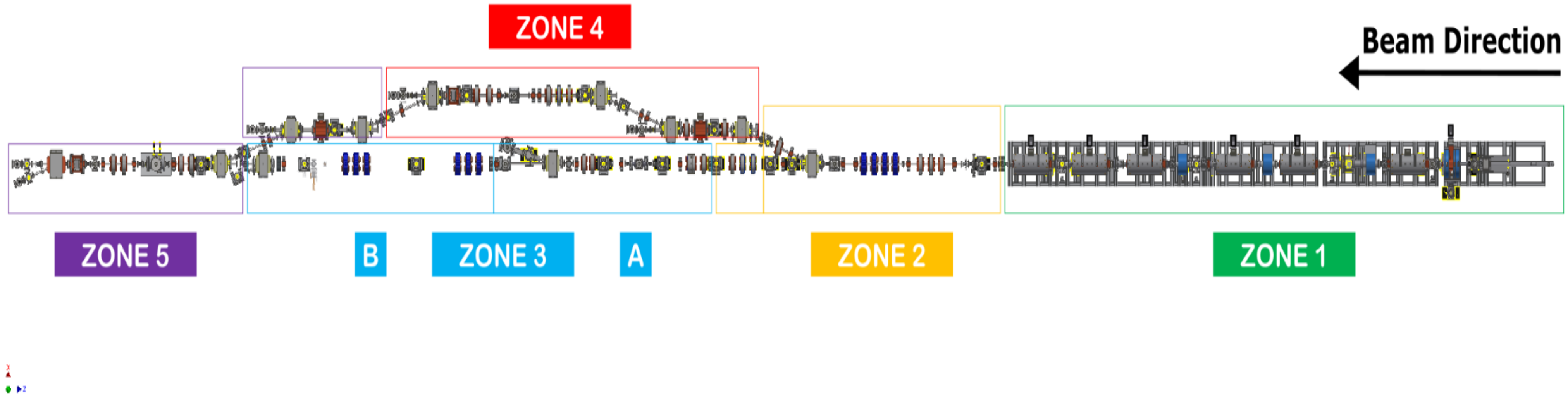
Laser undulator gives low energy operation (<46 MeV)

CXFEL Soft X-ray Parameters

Photon energy	250	1000	2500	eV
X-ray wavelength	4.9	1.2	0.49	nm
Average flux at 1 kHz	8.0E+11	1.1E+11	4.4E+10	photons/sec
Average brilliance	1.3E+15	1.2E+16	7.3E+16	ph/s/mm^2/mrad^2
Peak brilliance	1.2E+28	5.6E+28	1.4E+29	ph/s/mm^2/mrad^2
RMS source size	0.9	0.5	0.3	um
RMS source divergence	440	188	117	urad
X-ray flux per shot - energy	32	18	18	nJ
Photons per pulse	8.0E+08	1.1E+08	4.4E+07	Photons/shot
Pulse length FWHM	9.1	4.6	1.9	fs
Bandwidth FWHM	0.18	0.09	0.08	%
RMS timing jitter	<10	<10	<10	fs
Repetition rate	1000	1000	1000	Hz
Electron beam energy	14	29	46	MeV

Goals extending to sub-nanometer coherent light

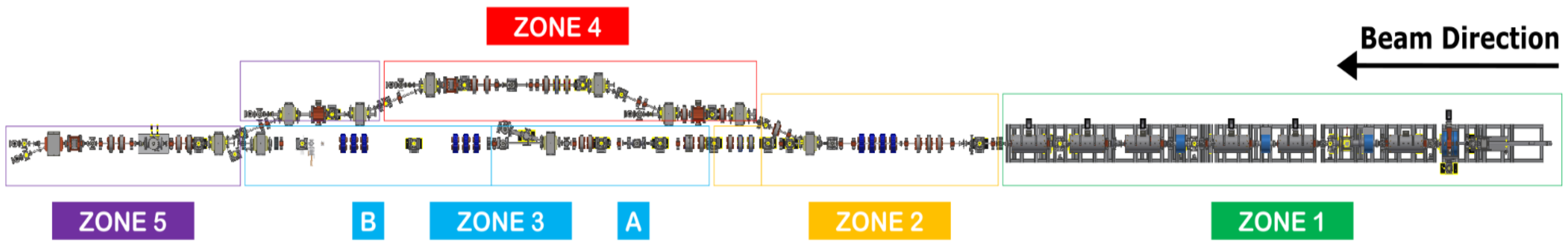
This collaboration has embraced an experimental opportunity at the AWA



Test the physics limiations of the EEX microbunching itself

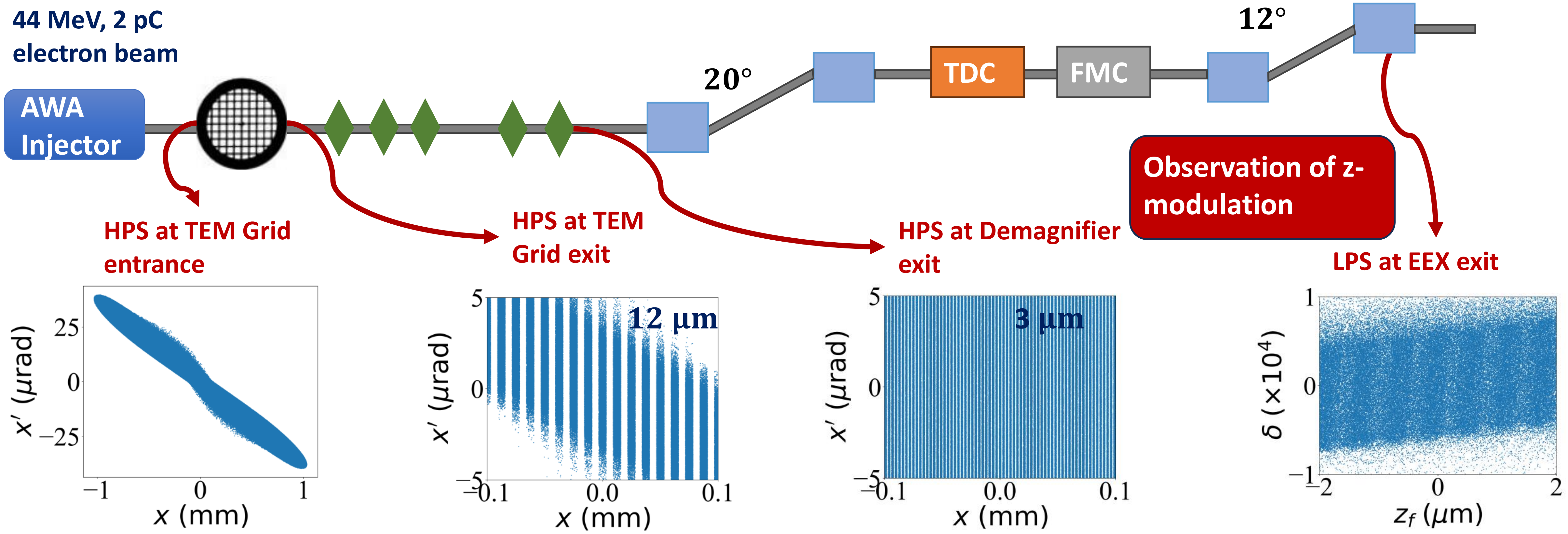
Micro-bunching with EEX at the AWA

- Start at longer period modulations
  - Collimation-based systems; ASU uses electron diffraction
    E. A. Nanni, W. S. Graves, D. E. Moncton Phys. Rev. Accel. Beams **21**, 014401 (2018)
  - Diagnostic systems within reach?
  - Establish operation in optical-IR – 800 nm
- Explore physical limits of process in existing setup
  - Optical nonlinearities
  - **Collective effects**: space-charge, coherent synchrotron radiation (CSR)
- First analysis of physics and experimental challenges
  - Study charge, wavelength, optics dependencies
  - Initial experimental scenario can be scaled in charge



Overview of Experimental Approach

Goal: generate **sub-micron** longitudinal density modulation using (asymmetric) emittance exchange (EEX) beamline at the AWA



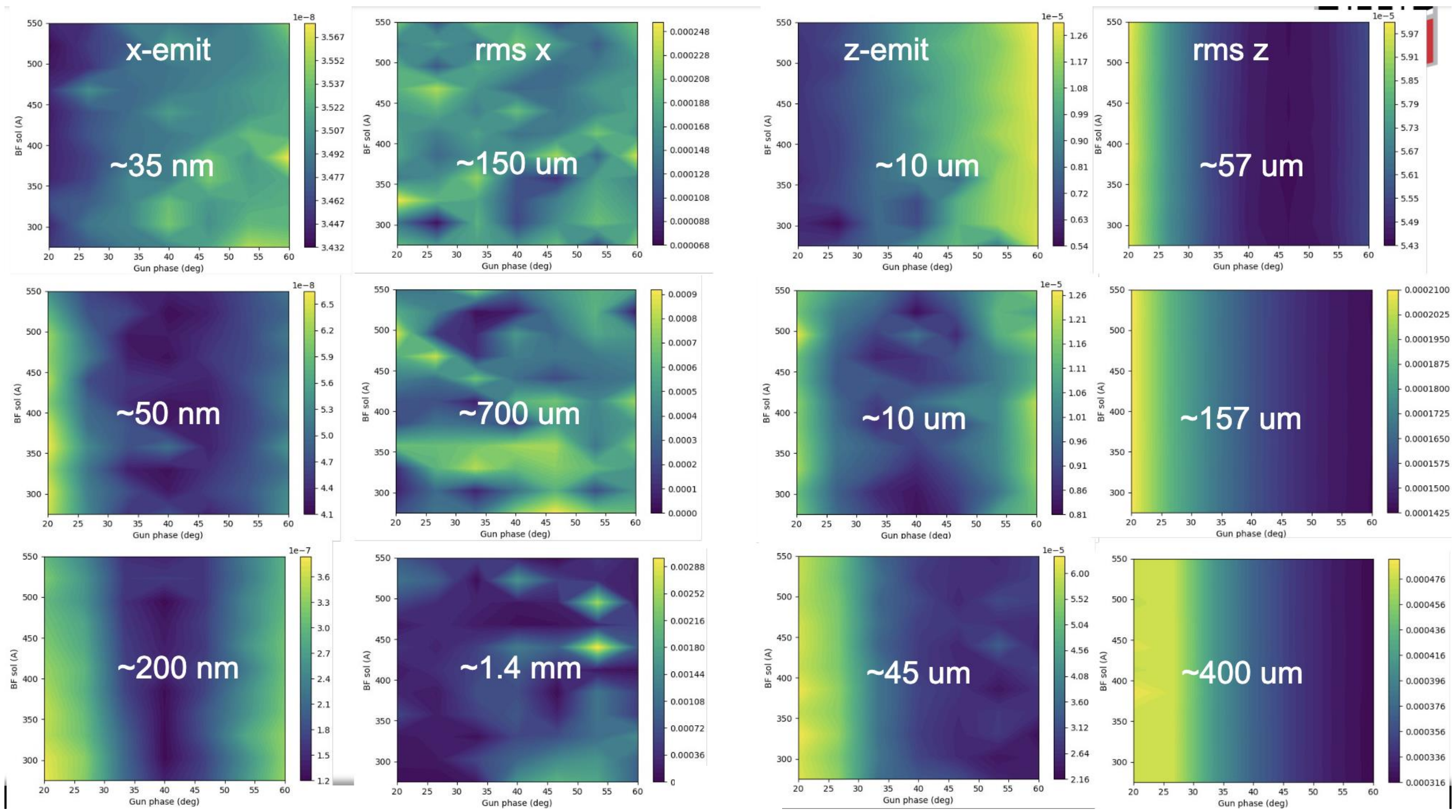
The beginning: low charge **(1 pC) operation** chosen

Low charge for many reasons! Emittance, EEX CSR and space-charge, nonlinearities

0.1 pC

1 pC

10 pC



Courtesy G.Ha

Optimized phase space quality; minimized collective effects

Emittance: quad scans

Non-optimized:
2025: old RF gun
2026: large laser on cathode

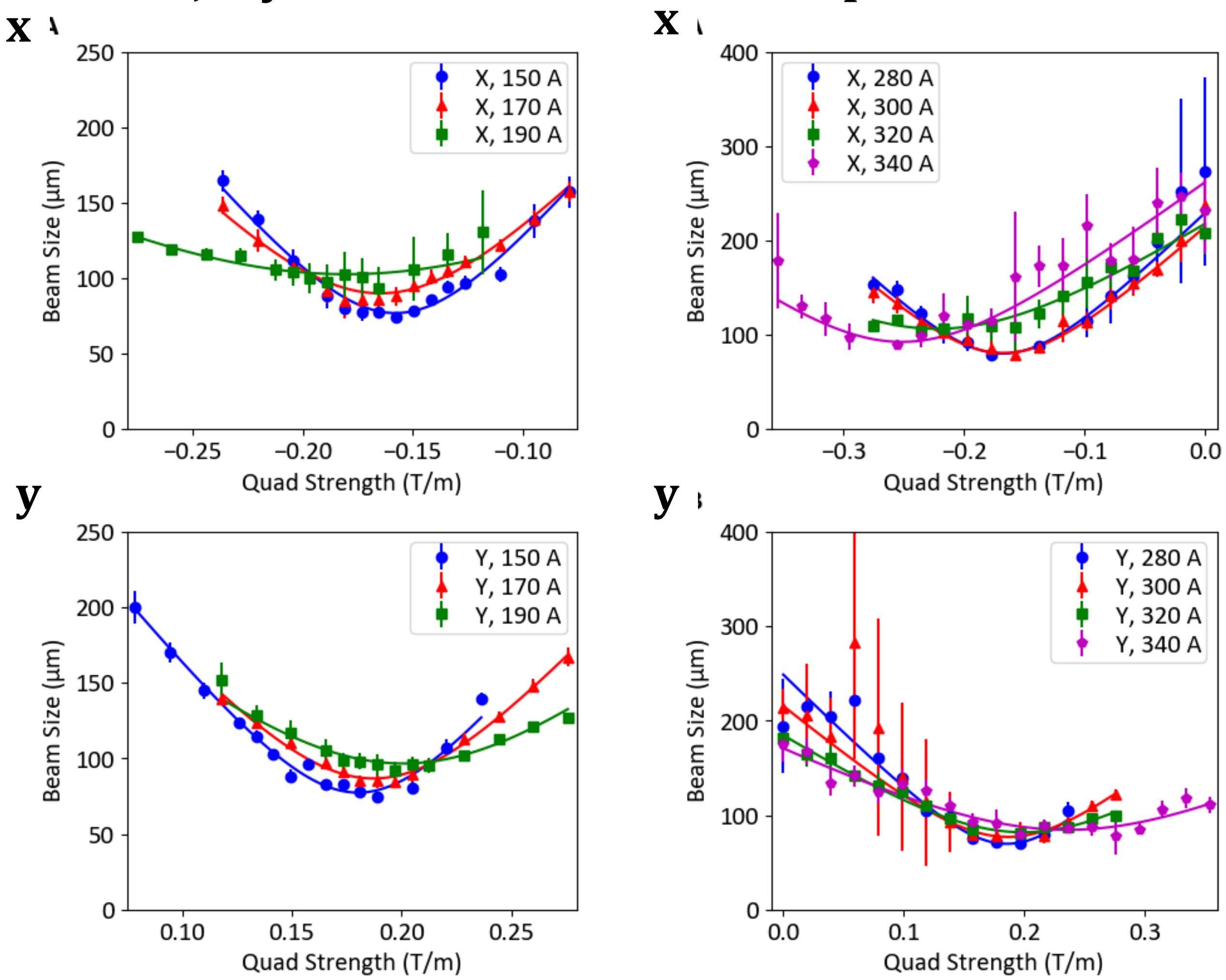
July 2025 Quadrupole Scan

Solenoid Current (A)	Charge (pC)	$\epsilon_{x,N}$ (nm*rad)	$\epsilon_{y,N}$ (nm*rad)
150	3	370 ± 20	390 ± 20
170	3	390 ± 20	400 ± 20
190	2.8, 2.7	220 ± 20	330 ± 20

April 2026 Quadrupole Scan

Solenoid Current (A)	Charge (pC)	$\epsilon_{x,N}$ (nm*rad)	$\epsilon_{y,N}$ (nm*rad)
280	1.2	280 ± 20	250 ± 20
300	1.2, 1.1	270 ± 10	230 ± 20
320	0.9	250 ± 20	190 ± 20
340	0.8	250 ± 20	150 ± 20

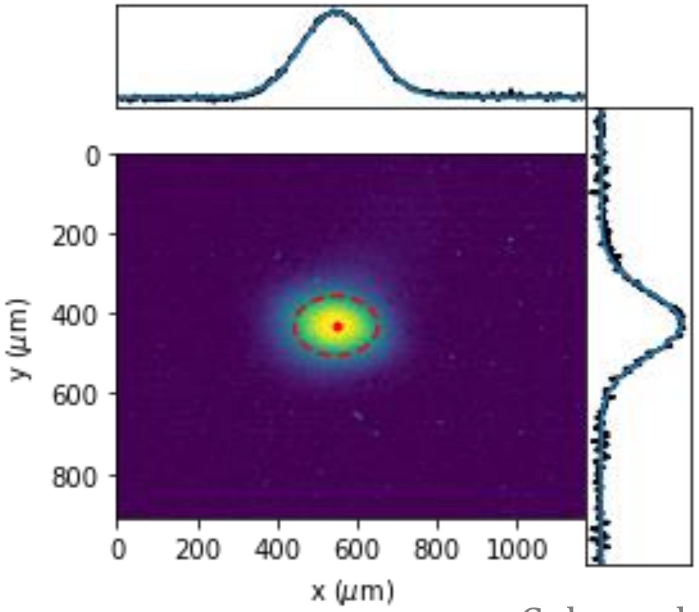
July 2025 April 2026



Courtesy R. Magraf-O'Neal

Measuring micron-scale beam features

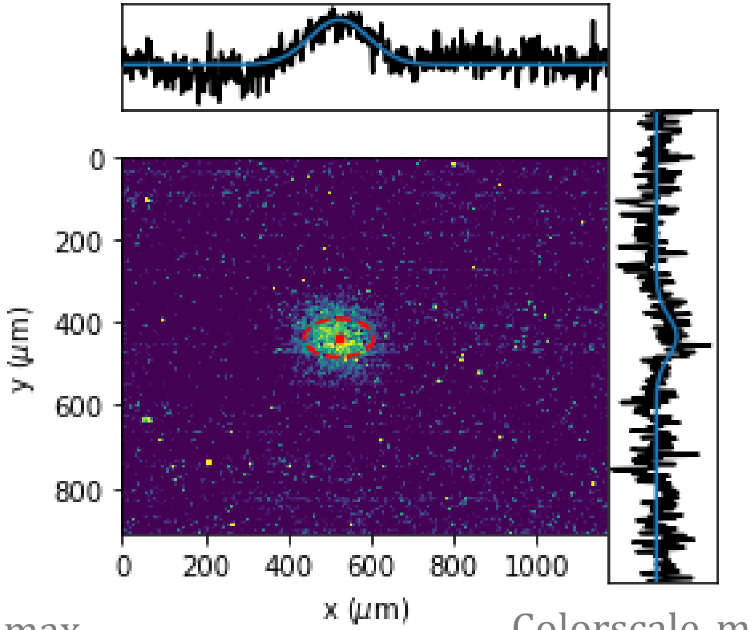
Filter 3.2% (3pC)



Colorscale_max =12000

σ_x = 89 μm
σ_y = 63 μm

Filter .32% (~.3 pC)



Colorscale_max =1000

σ_x = 71 μm
σ_y = 39 μm

Smallest beam sizes measured at AWA are 30-40 μm

- YAG thickness (100 μm) can reduce resolution
- Collective effects
- Emittance/beam-optics limits

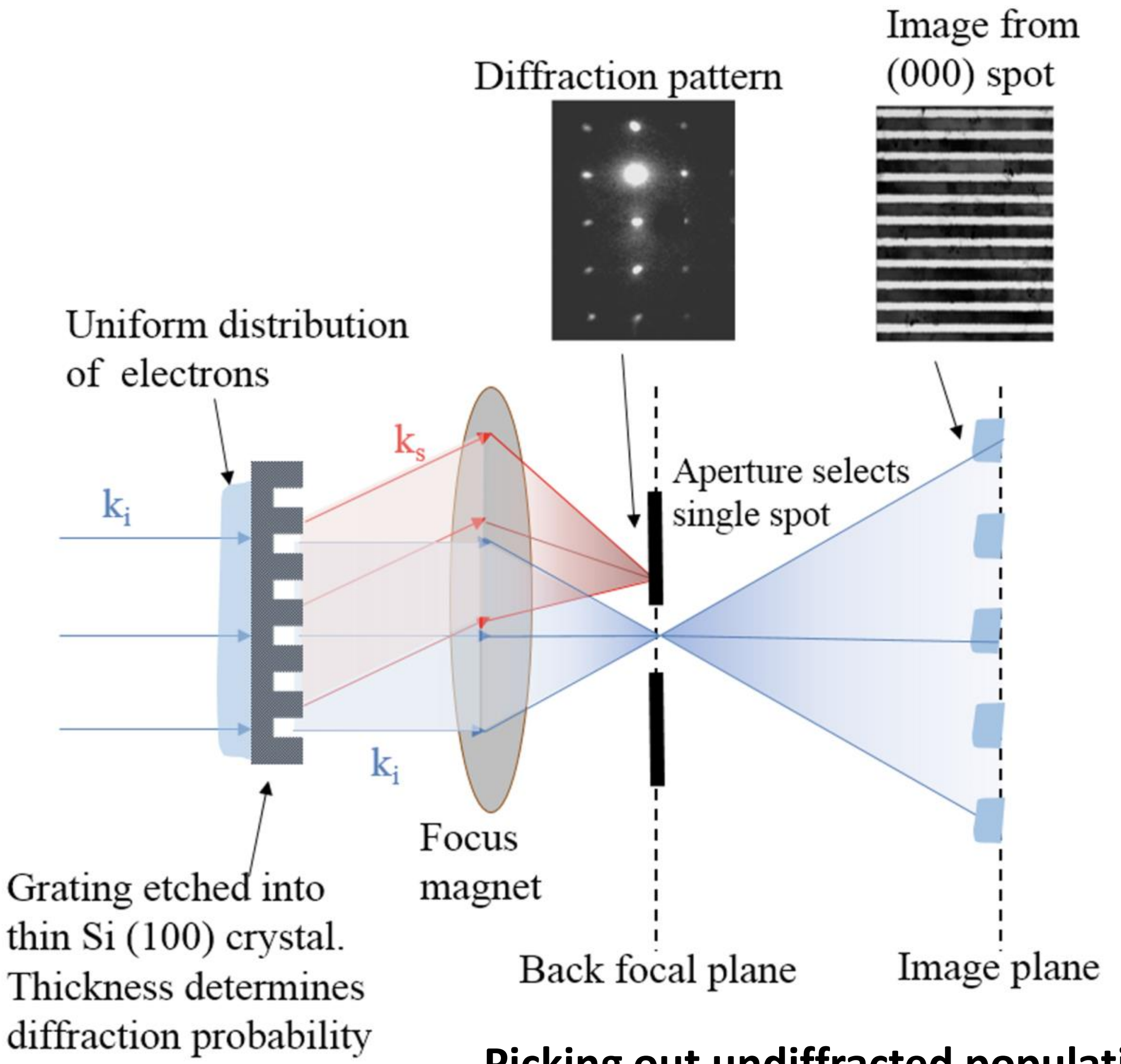
Courtesy R. Magraf-O'Neal

Micro-patterning: CXFEL uses *diffraction*

Use of optimized electron diffraction with structured Si (100) crystal

A complex process.

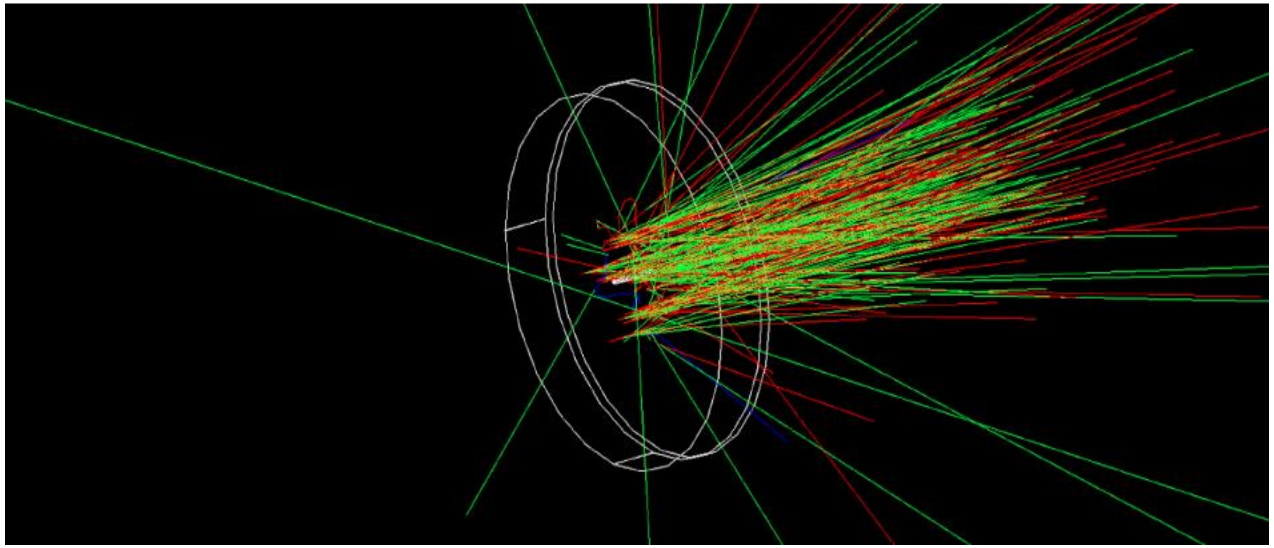
To begin, simplify…



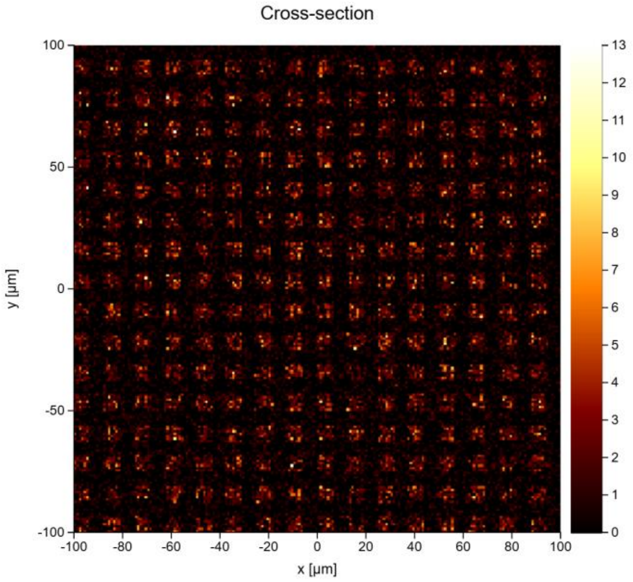
Picking out undiffracted population

TEM grid used for micro-patterning at micron level

- First step: 44 MeV electrons scatter on gold TEM grid with 12.5-62 μm periodicity wire array,. Simulated in GEANT4
- Follow with demagnification using quad triplets



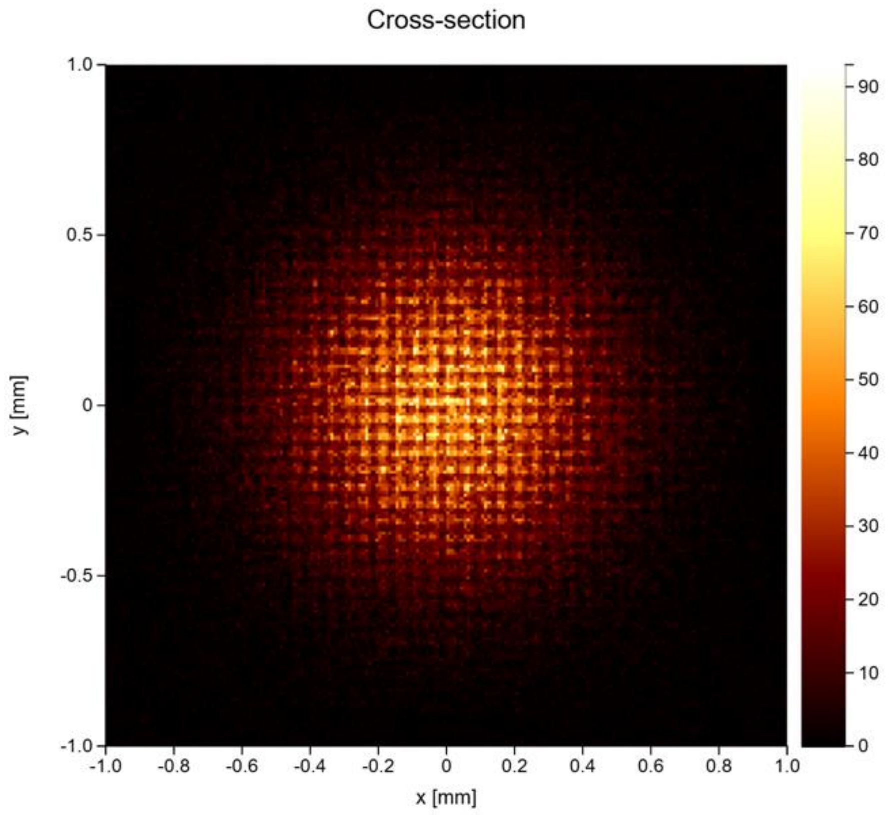
GEANT4 simulations



Beam image after 5 cm

Bonus: emittance measurement with TEM grid

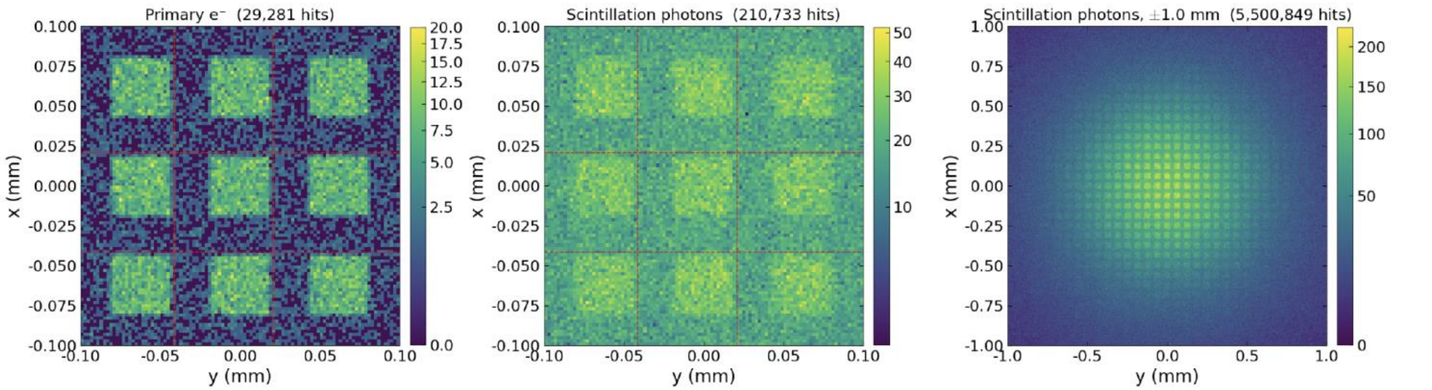
- First at high energy, 44 MeV (compare to UCLA Pegasus at ~4 MeV)
- Image 50 cm after grid shows angular spreading after collimation
  - Is it too much spreading? Shorten drift
  - How high of emittance is measurable?



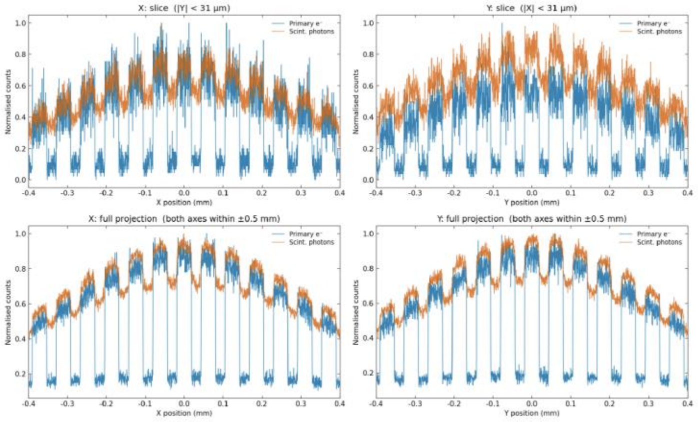
Beamlet spread gives 4D phase space

Recent analysis more detailed

- Close coupling (5 cm) of grid and YAG detector – bremsstrahlung directly excites YAG emission
- Problem for initial validation of the transverse modulation
- Boundary condition for emittance measurements



Electron beam pattern



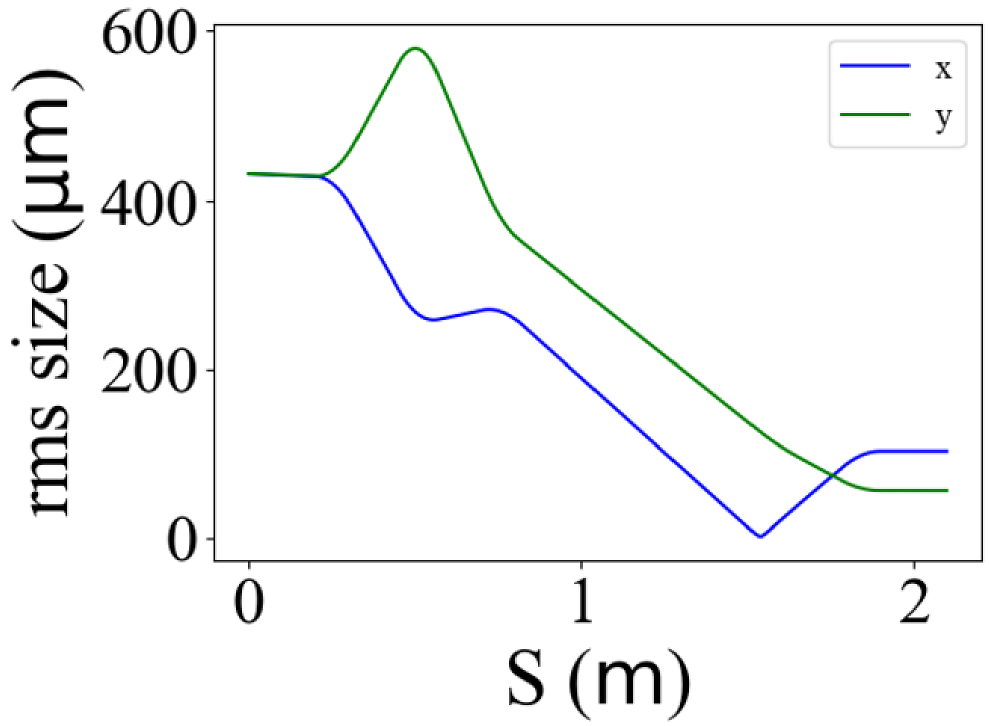
Emission at YAG surface

Courtesy Jack Phillips

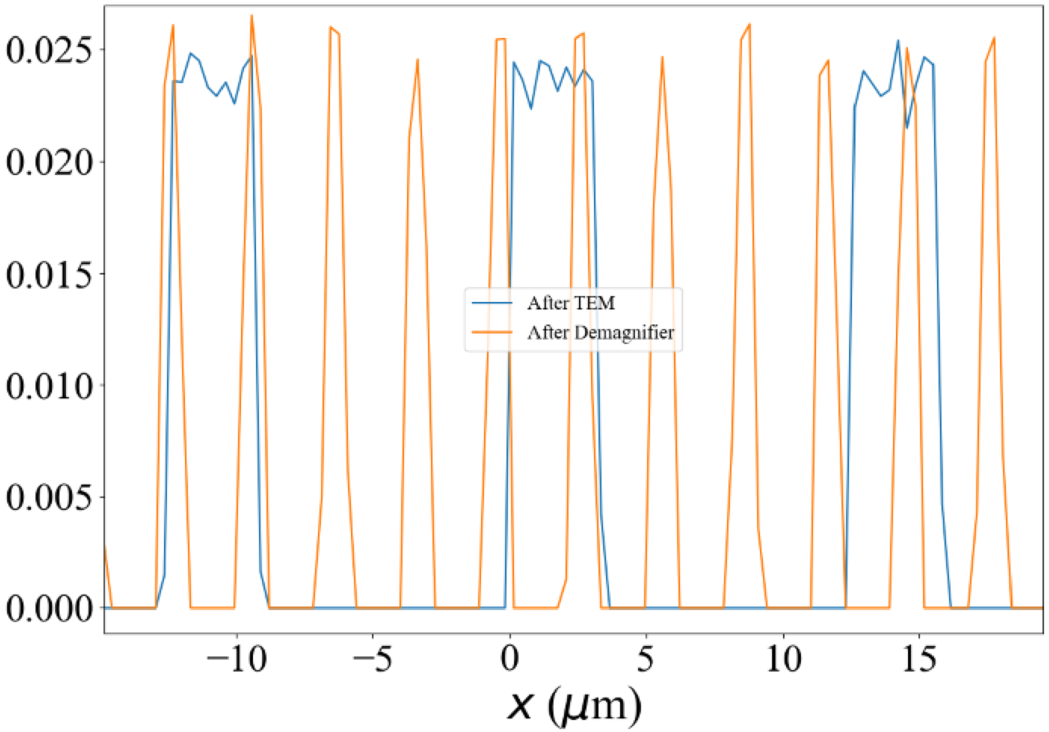
Demagnification section

Courtesy Buse Naz Temizel Ozdemir

Demagnification section



Modulation befor and after demagnification



3 microns x periodicity ->0.8 nm in z periodicity w/EEX

We have simulated up to 8.3x demagnification. More demag occurs in EEX

Sextupole Correction of 2nd order non-ideal behavior

Placed 2 sextupoles at the best candidate locations;

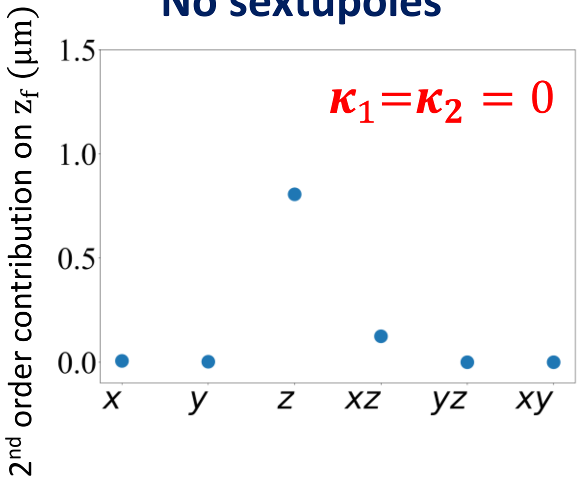
- Sextupole at DL2 entrance mainly affects **z-series**, with less impact on **xz-series.**
- Sextupole inside DL2 affects **xz-coupling** more.
- Combining both sextupoles enables control of all dominant second-order terms.

z: $\sqrt{\langle (T_{555} z^2,\ T_{556}\, z\delta,\ T_{566}\delta^2)^2 \rangle}$

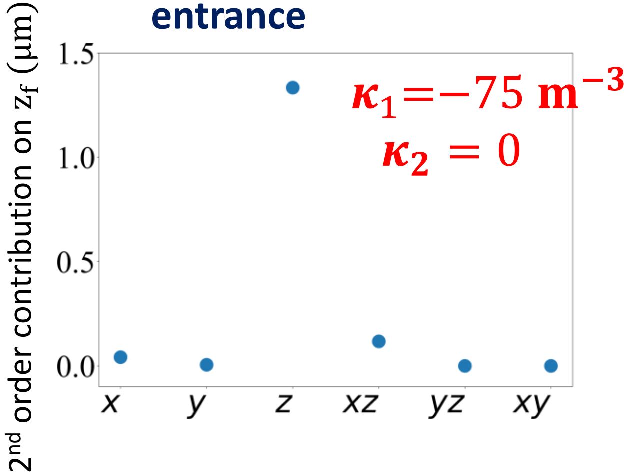
xz: $\sqrt{\langle (T_{515} xz,\ T_{516} x\delta,\ T_{525} x'z,\ T_{526} x'\delta\,)^2 \rangle}$

Isolates degradation from collective effects

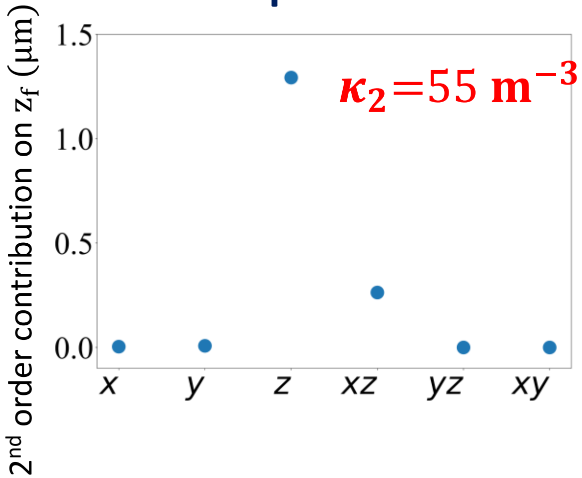
No sextupoles



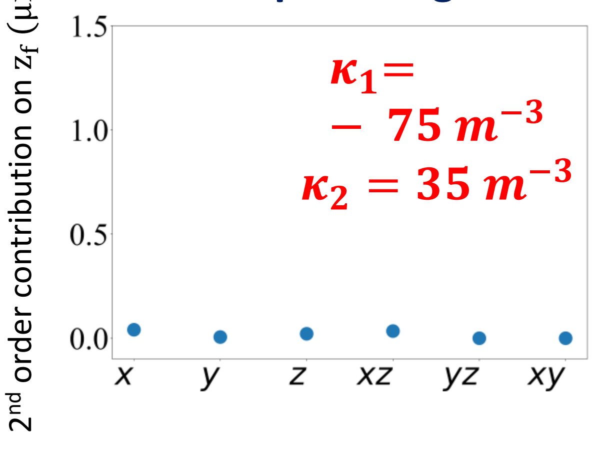
A sextupole at DL2 entrance



A sextupole in DL2



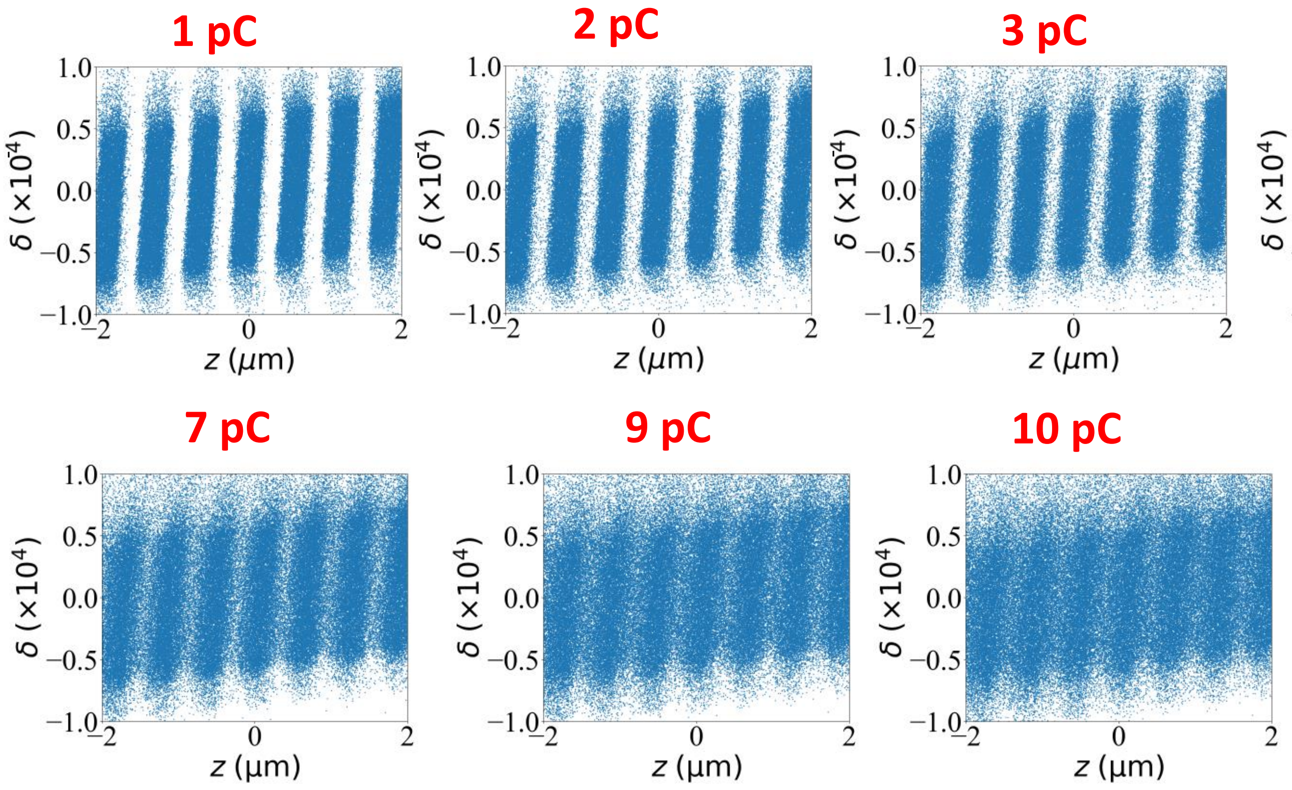
2 sextupoles together



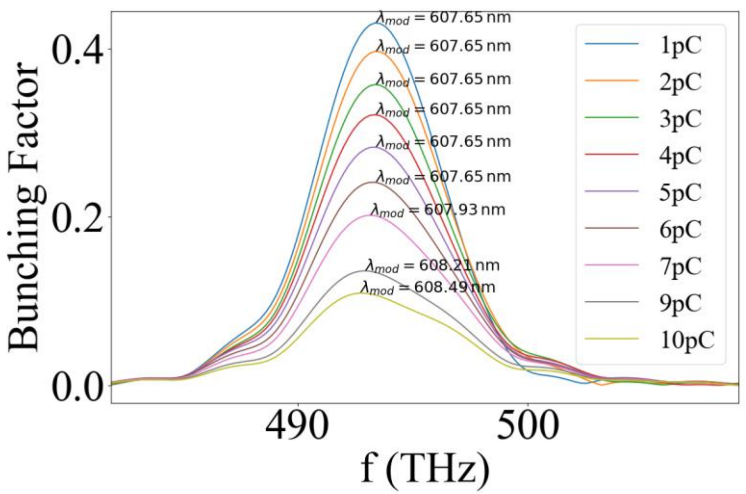
Effect of Beam Charge on Bunching Factor and LPS

Scanned charge to see its effect on the modulation. Notable distortions above 3 pC

LPS for different charge levels



Bunching factor for different charges



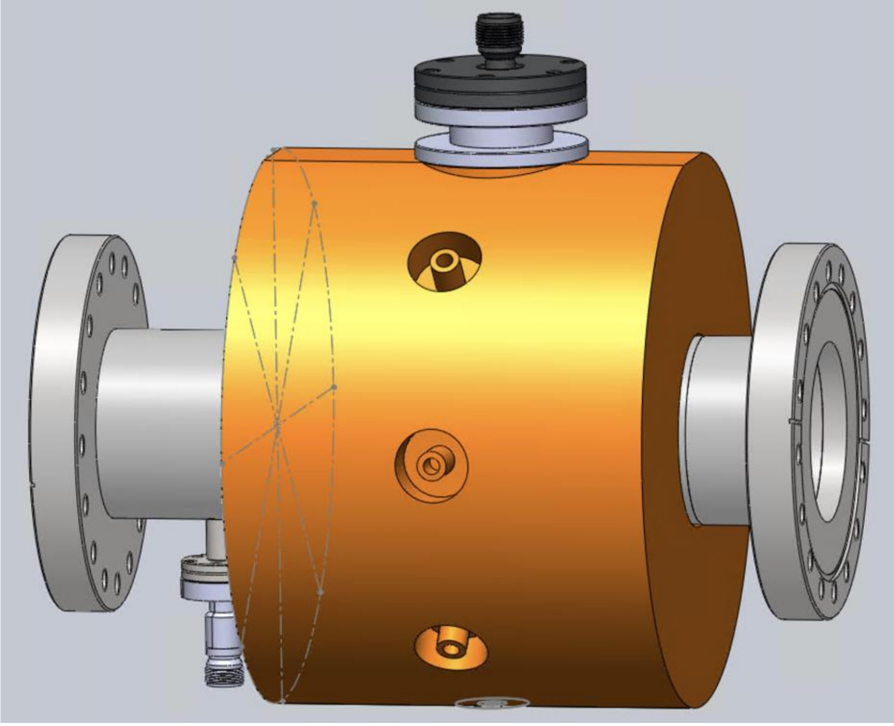
Bunching factor remains measurable at higher beam charge

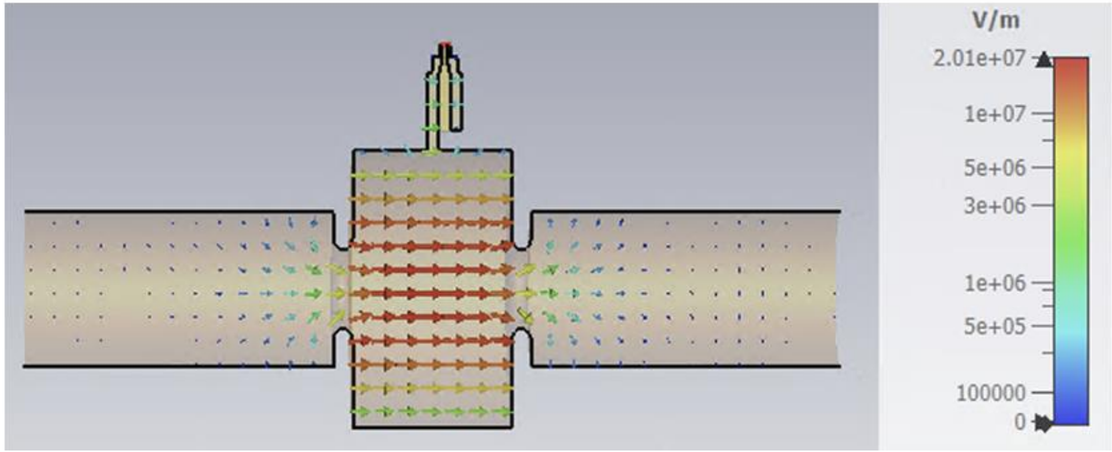
To do: remove correlations

Courtesy Buse Naz Temizel Ozdemir

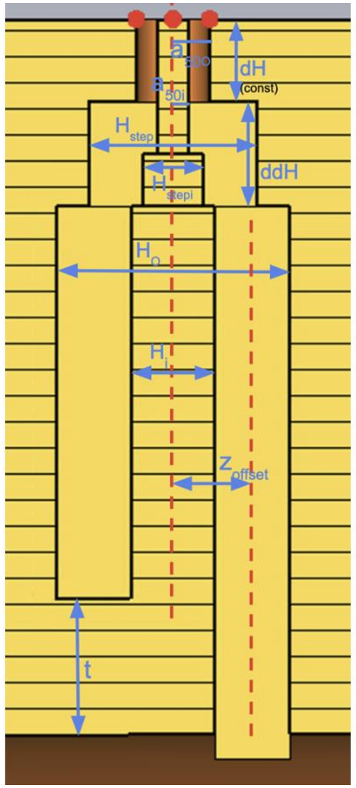
Fundamental mode cavity development

- Single cell, 300 kV for correction . Power only10-20 kW
- Joint design effort (LANL/ASU/UCLA) with UCLA fabrication. Synergistic with LANL development





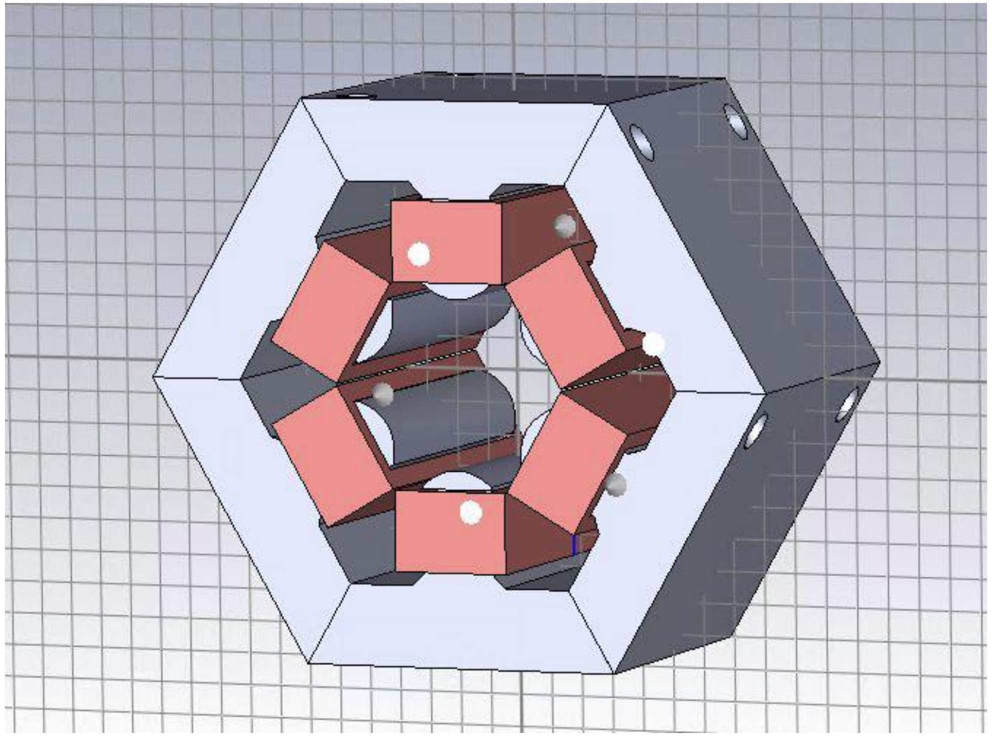
Electric ield profile

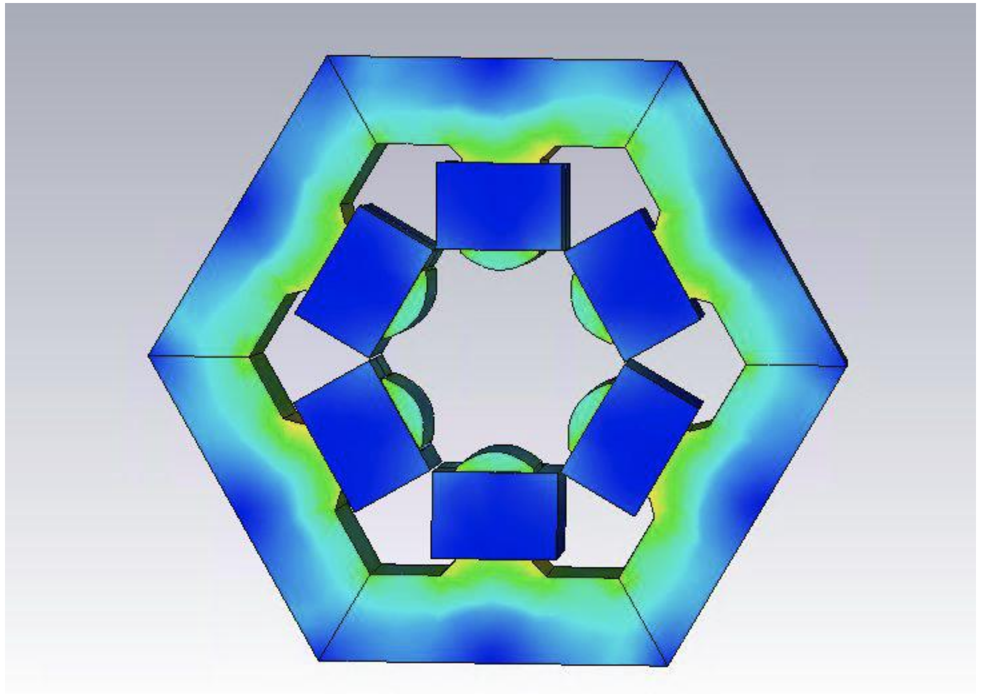


Novel coaxial coupler

Sextupole design

- Like FMC, fields are weak, but apertures are large (2 inch beampipe in EEX
  - Need only ~60 T/m^2
  - Current limited, changing coil geometry





Measuring microbunching

- 3 micron modulation yields 800 nm microbunching
  - Coherent radiation measurement
  - Copious existing optics/detectors
- Use CTR; method well established
  - Far IR to optical
  - 800 nm *and harmonics* at VISA

A. Tremaine, et al. Phys. Rev. Lett. **81**, 5816 (1998)

- ~1E6 800 nm photons for this expt.
- Coherent radiation
  - UCLA-Kurchatov undulator

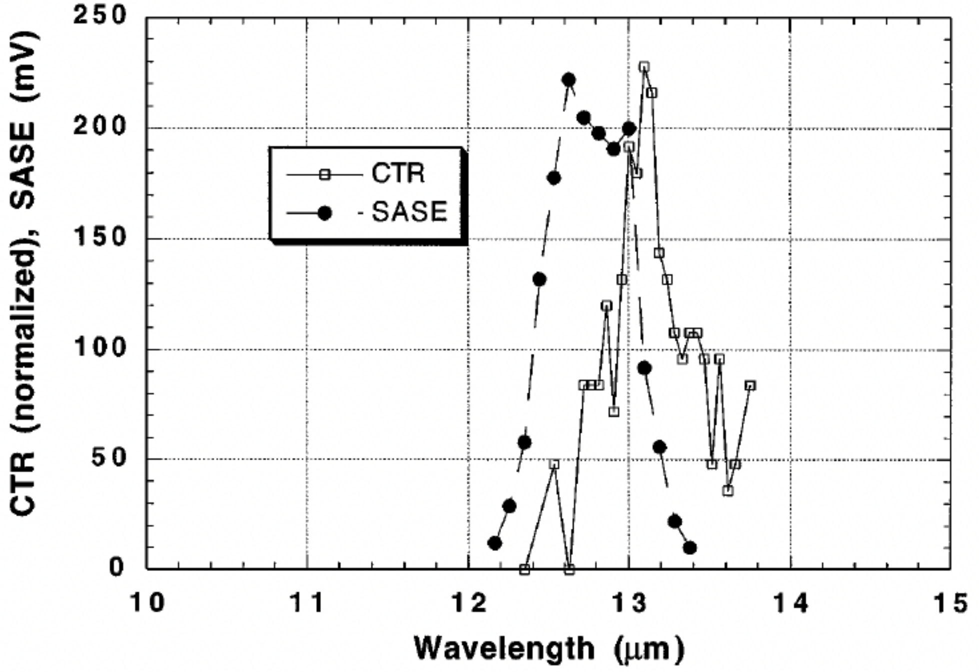
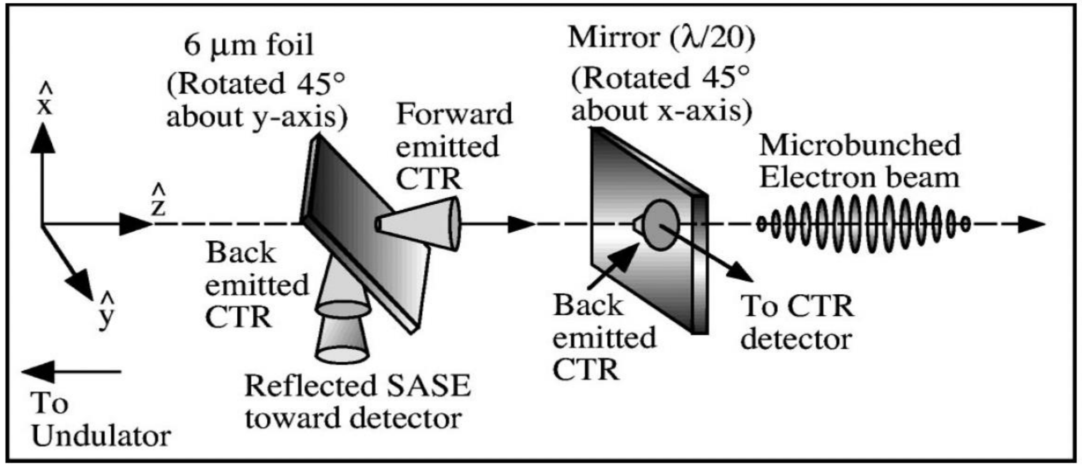


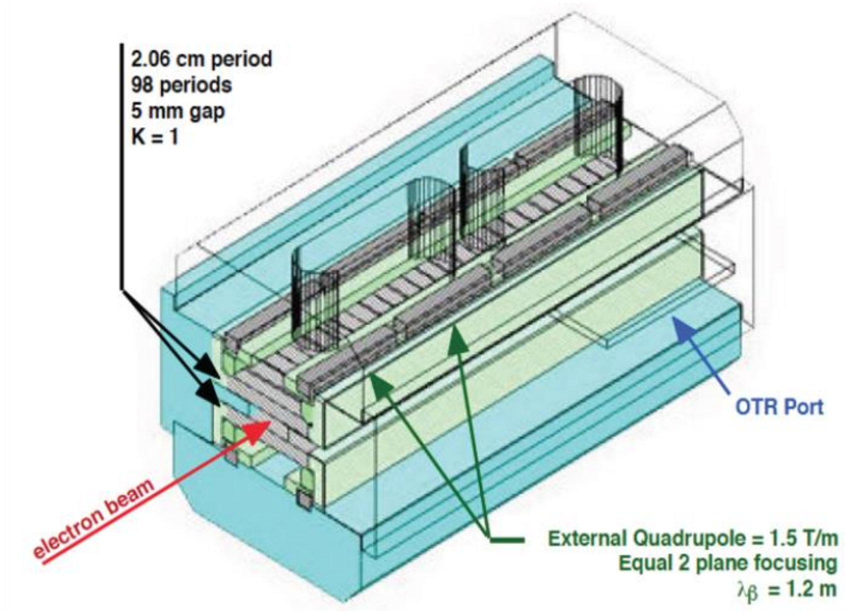
FIG. 3. SASE and CTR signals as a function of wavelength, with CTR scaled to SASE amplitude.

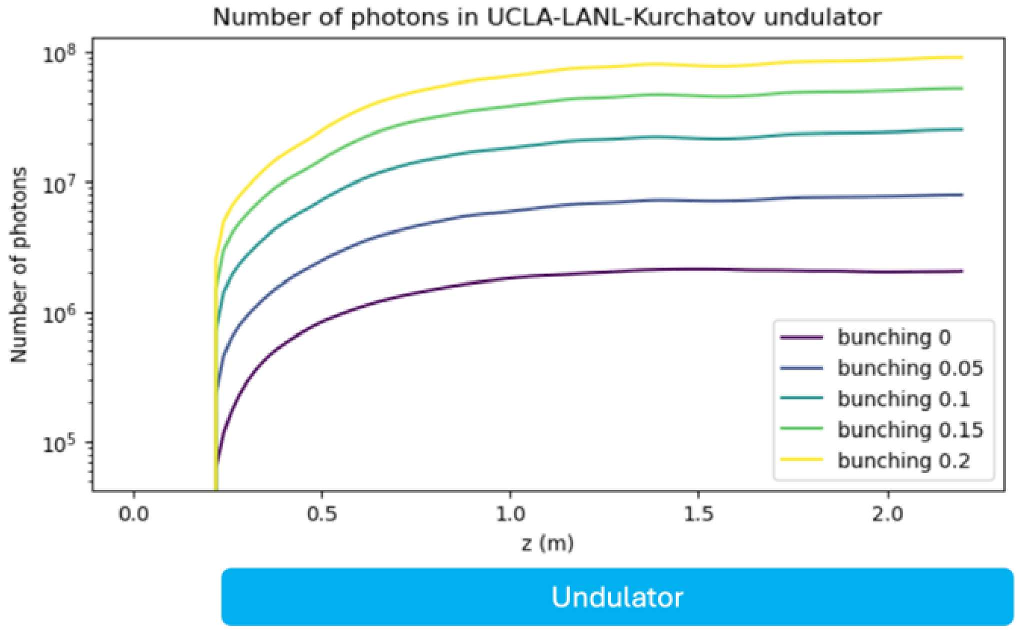
First high gain SASE microbunching diagnosed with CTR



Coherent undulator radiation

- UCLA undulator – 1E8 photons!
- Harmonics and gain to be investigated





AWA experiment on EEX-based micro-bunching

- Critical test of new ultra-compact light source schemes
- Beam dynamics analysis well underway
  - CSR and nonlinearities limits
  - Space-charge with GPT (also
- Interesting challenges in beam size measurements
  - Micron scale beams with large full ROI
  - Radiation and collective effects active
- EEX-based experiments beginning
  - Demagnification
  - Emittance measurements
  - New hardware
  - EEX commissioning
- Exciting program; heavy student involvement. Open collaboration

Thanks to US DOE BES for suppor t