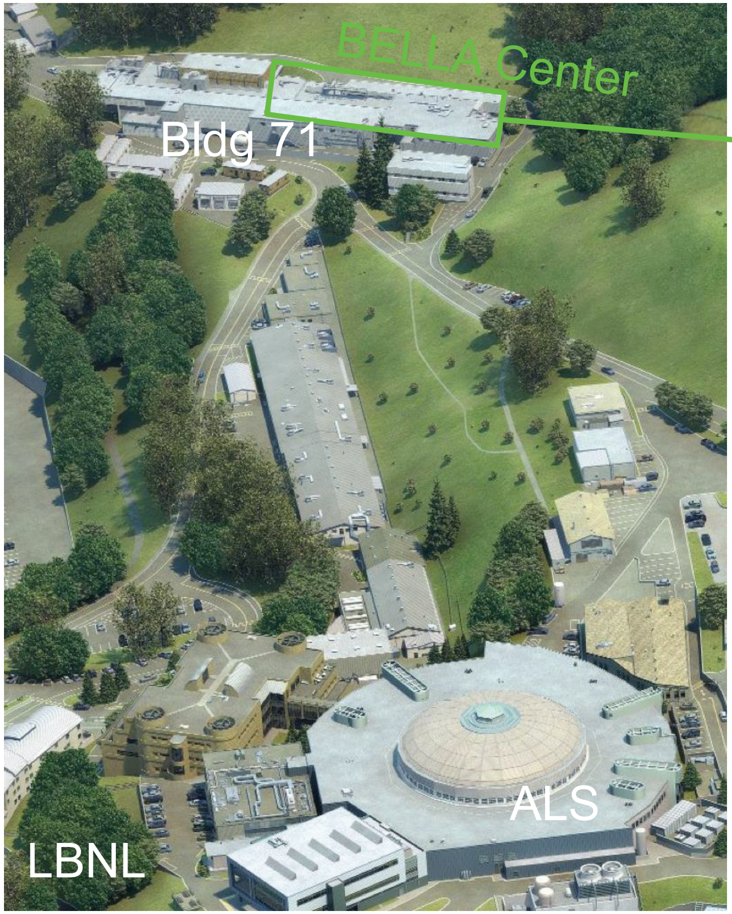
# Progress towards BELLA Center's Free Electron Laser driven by a Laser Plasma Accelerator

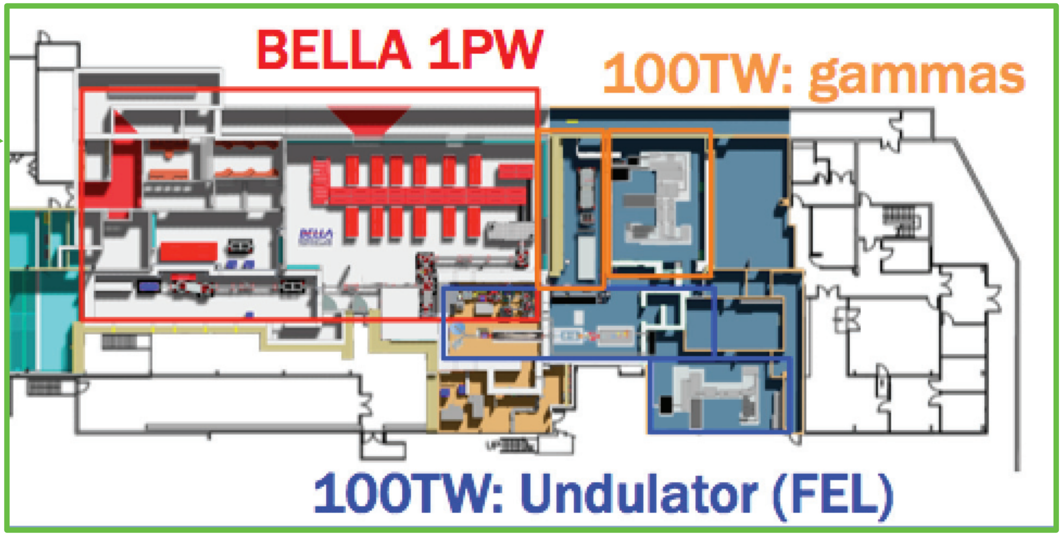
Jeroen van Tilborg, BELLA Center

Lawrence Berkeley National Laboratory

Future Light Sources, March 6th 2018

# BELLA Center pre-2017: BELLA PW & TREX 100 TW
# >2017: TREX replaced by 100TW Thomson scattering & 100TW FEL



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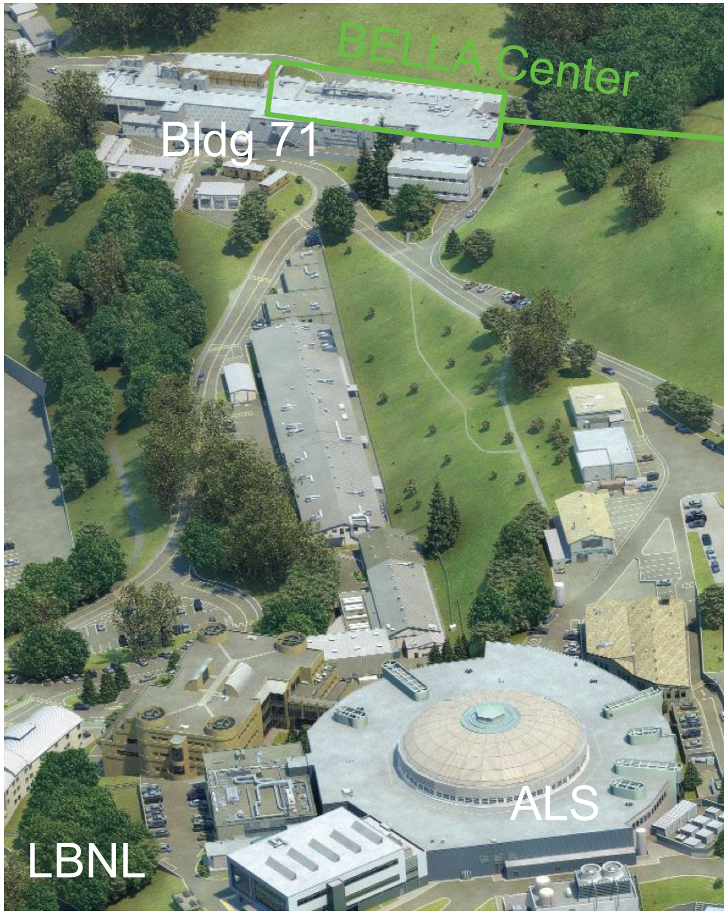


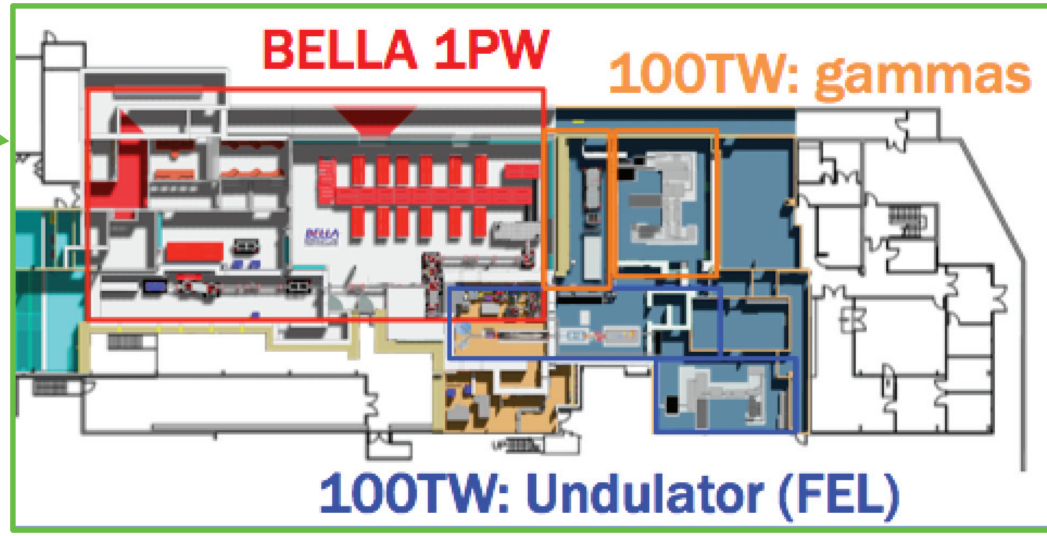




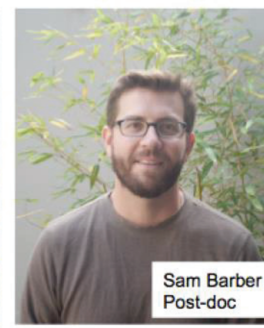


FEL team



Jeroen van Tilborg
Staff scientist
LPA FEL lead

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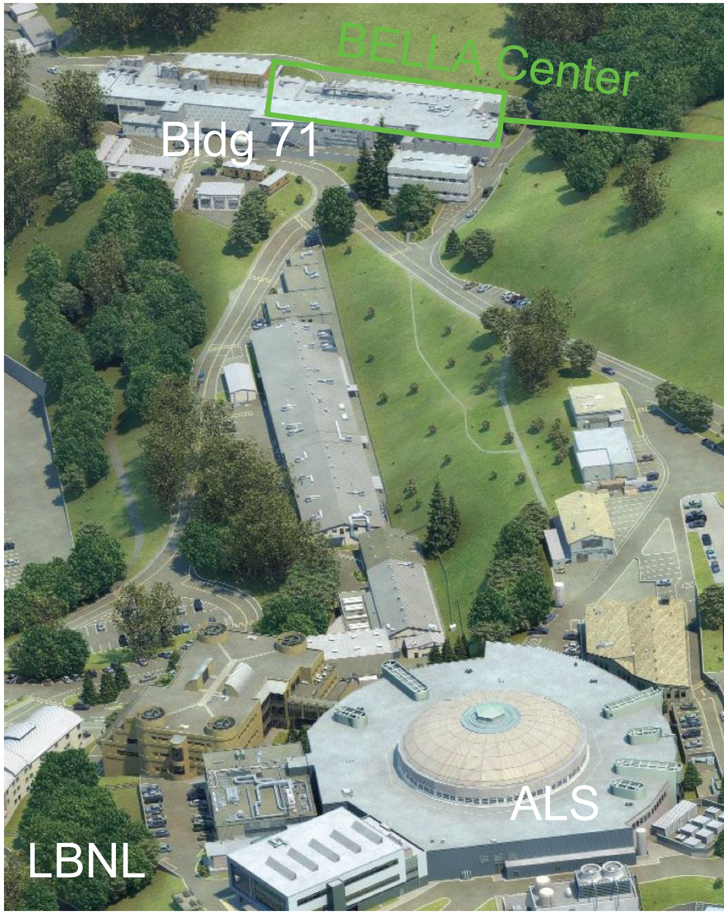


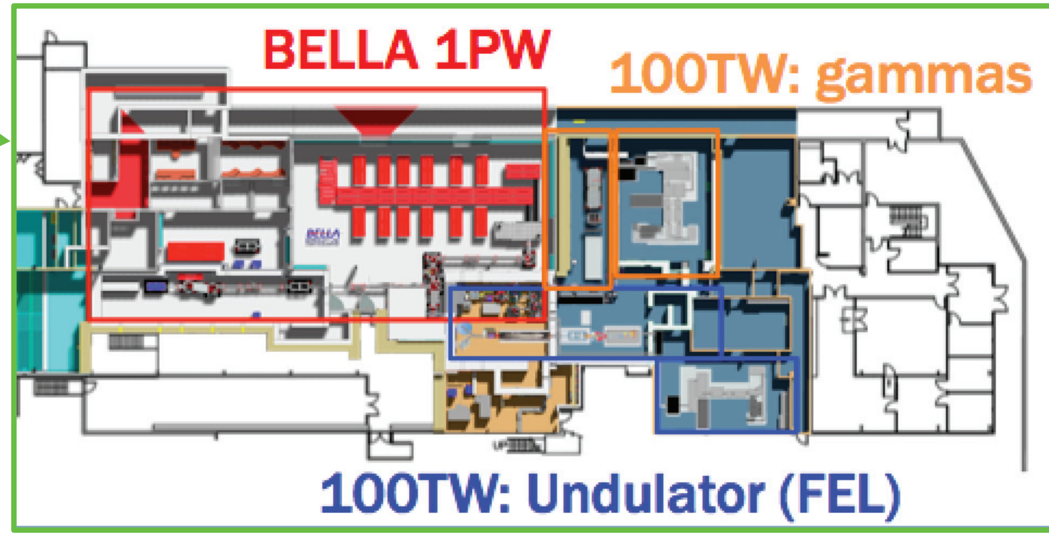




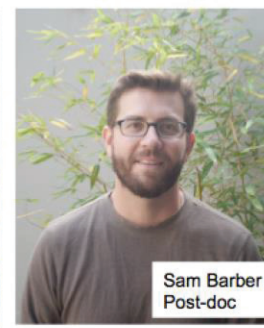


FEL team

- LPA FEL project: design & simulations
- Results: jet-blade LPA
- Results: Active Plasma Lens
- Results: Emittance measurements
- VISA undulator
- LPA FEL facility



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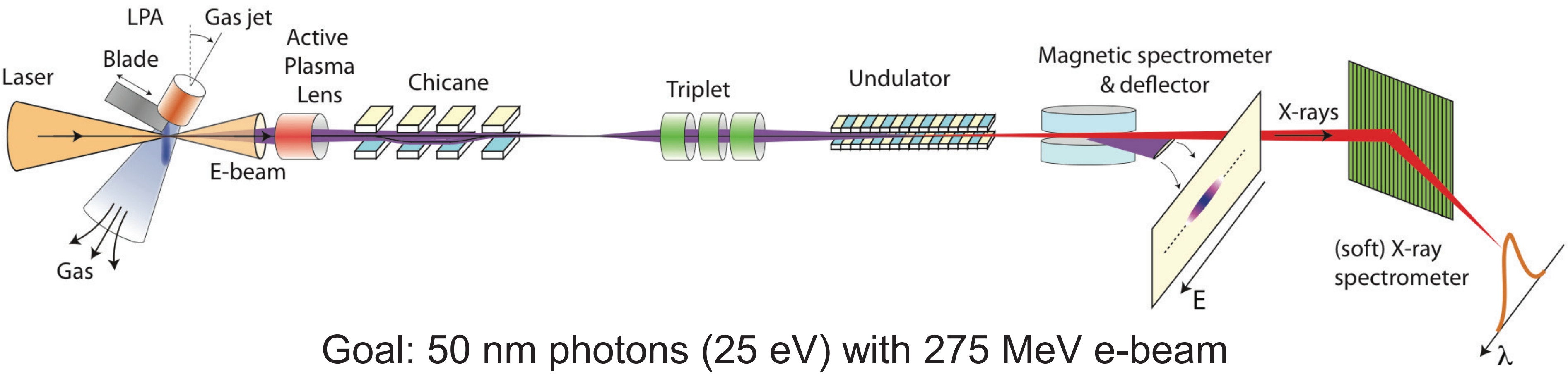
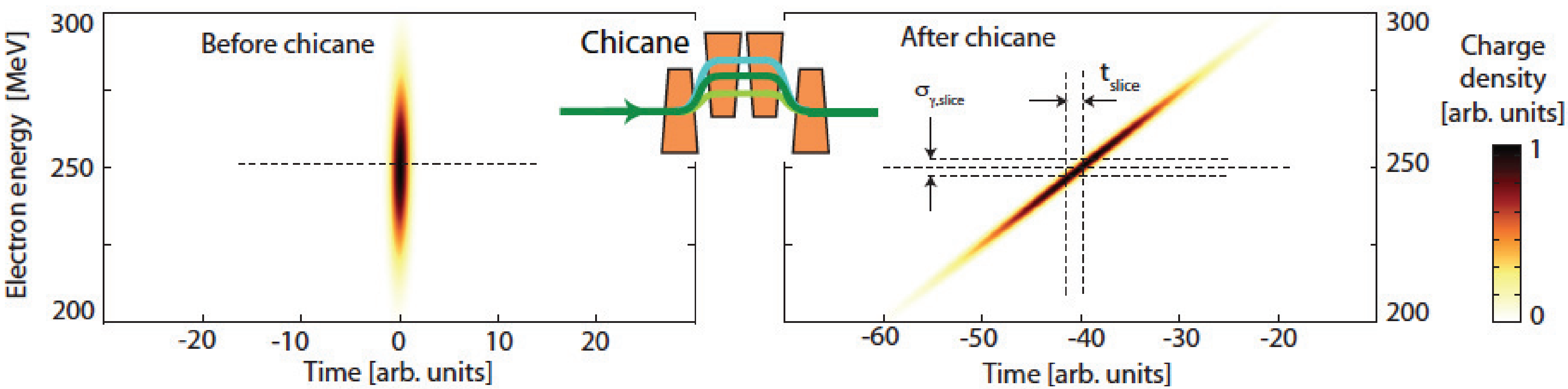
# Rapid beam capture, chicane, and EM triplet: matching to VISA undulator with embedded FODO lattice




Goal: 50 nm photons (25 eV) with 275 MeV e-beam

Use chicane (collaboration Rosenzweig, UCLA) to reduce slice energy spread

Maier *et al.* PRX 2012, Schroeder *et al.* FEL2013



# Details of transport and collective effects are important to understand performance goals

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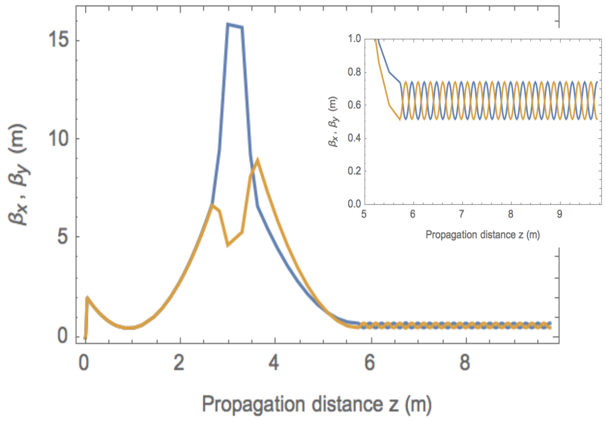

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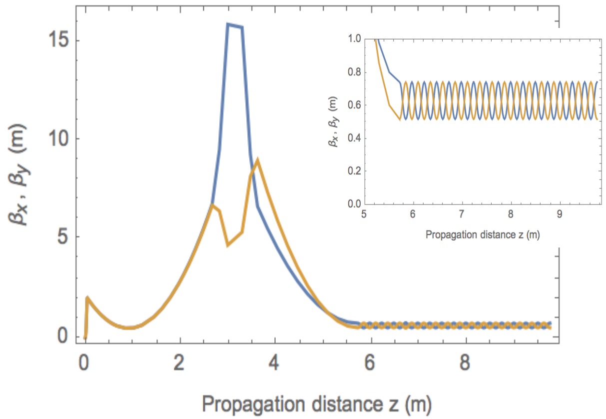


M. Borland LS-287. , 2000.

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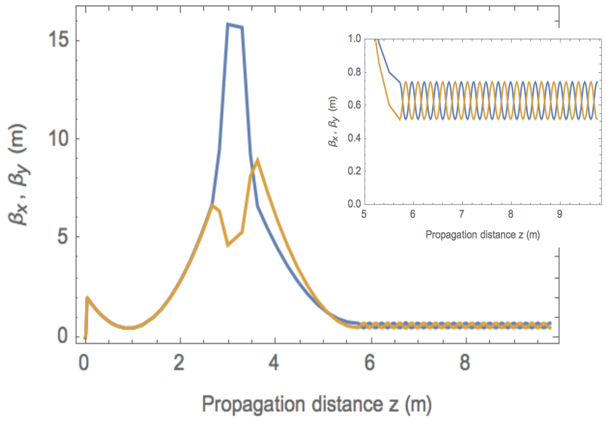


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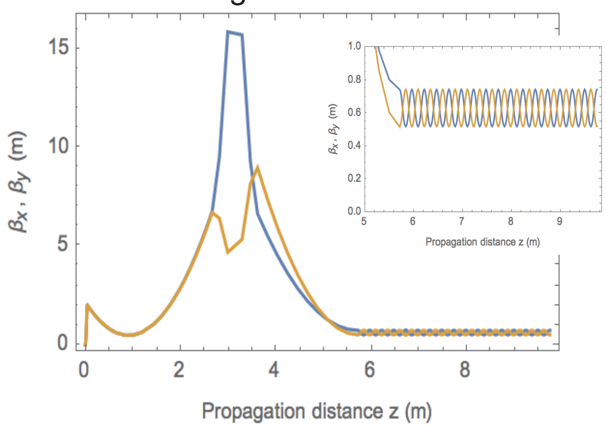


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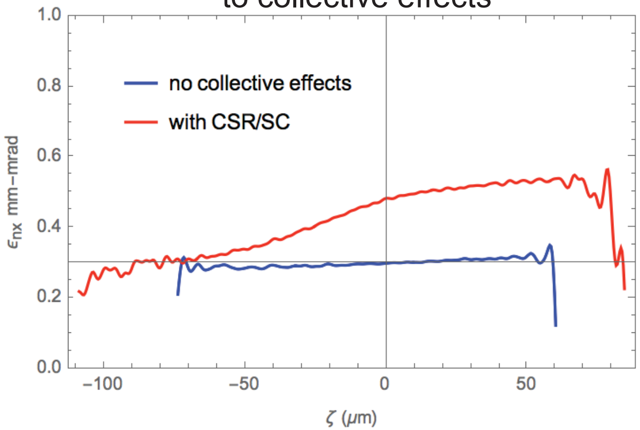
Slice emittance growth due to collective effects



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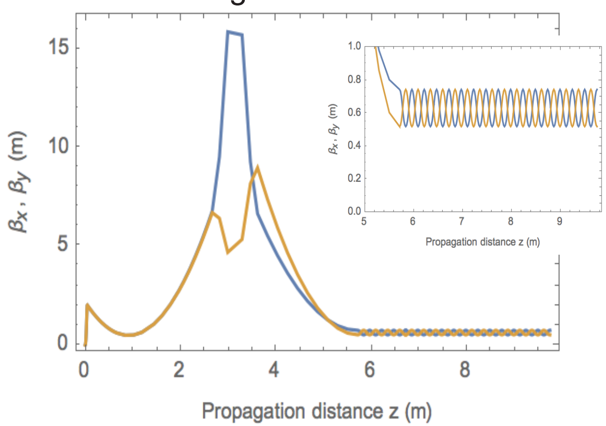


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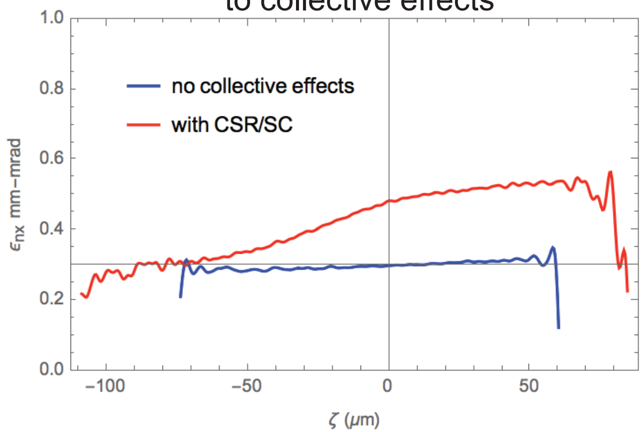


http://www.desy.de/~mpyflo/

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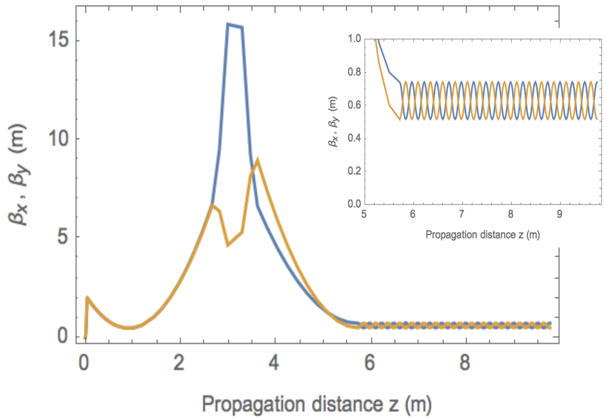


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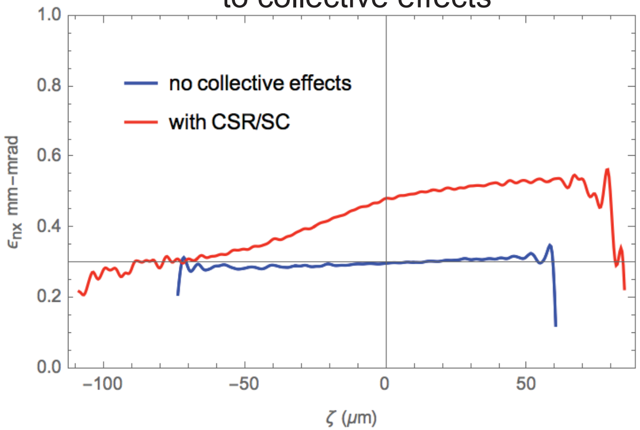


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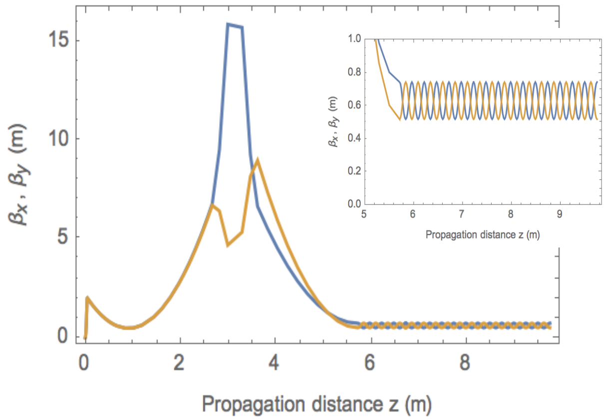


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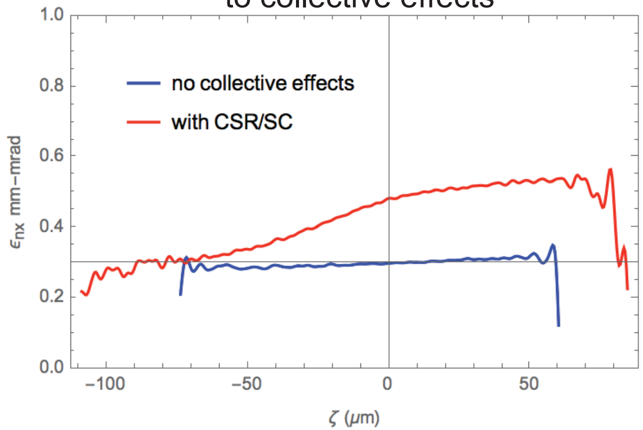


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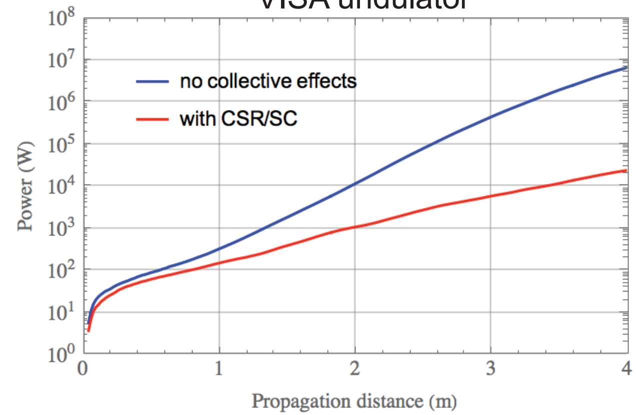
Peak power vs. distance in VISA undulator



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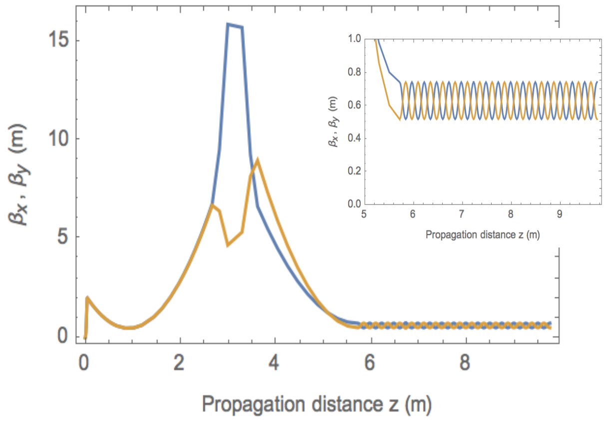


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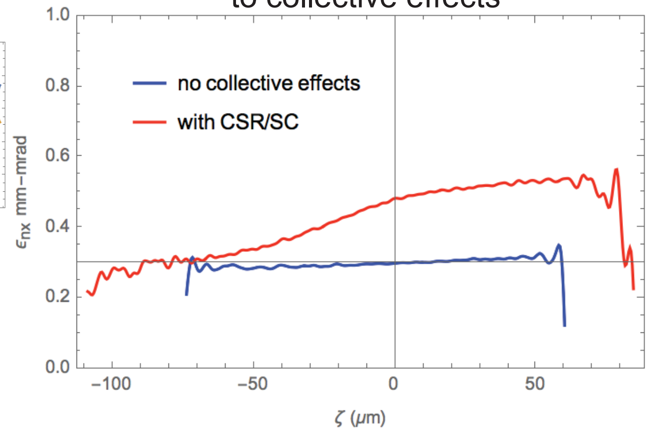


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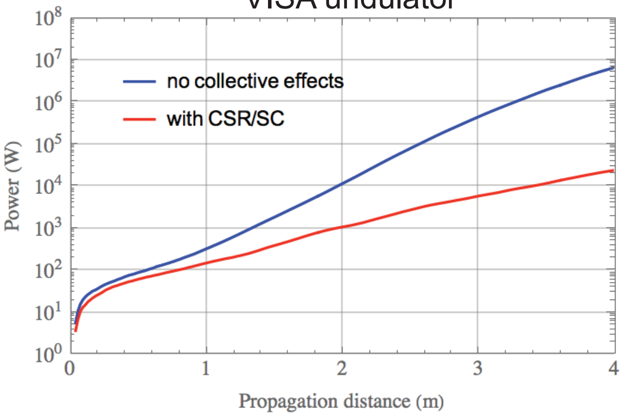
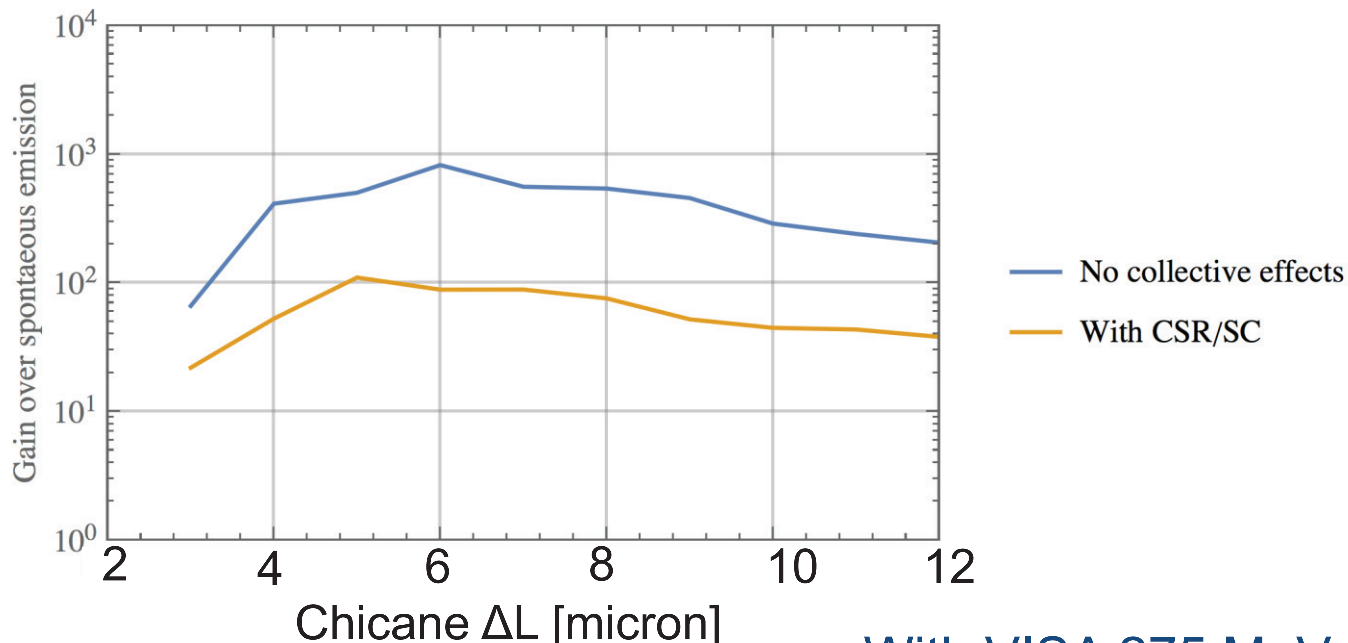



S. Reiche. NIMA, 429, 1999.

# High brightness LPA source coupled to properly designed transport enables compact FEL at EUV photon energies

High performance: 25 pC, $\sigma_\gamma = 1.0\%$, $\varepsilon_n = 0.3\ \mu m$, $\sigma_z = 1.0\ \mu m$

- Charge per percent energy spread is most important (less sensitive to variations in emittance)
- Gain in radiation power of order x100




With VISA 275 MeV→ $\lambda_l$=50 nm

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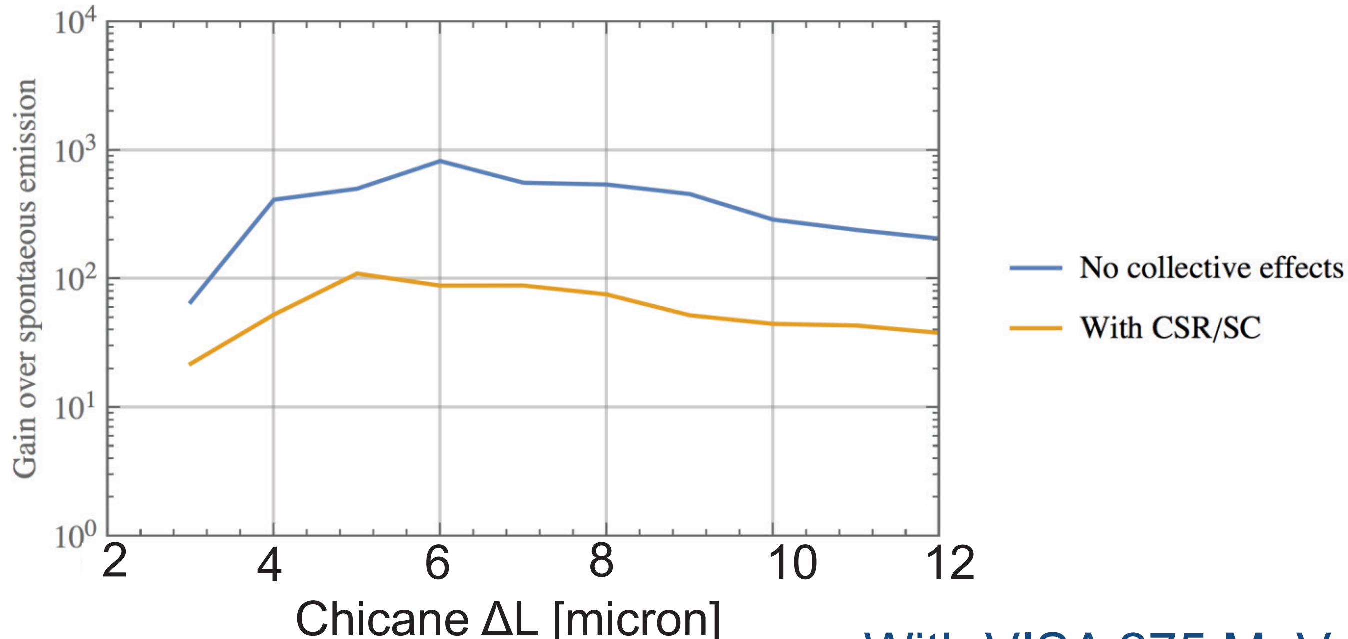
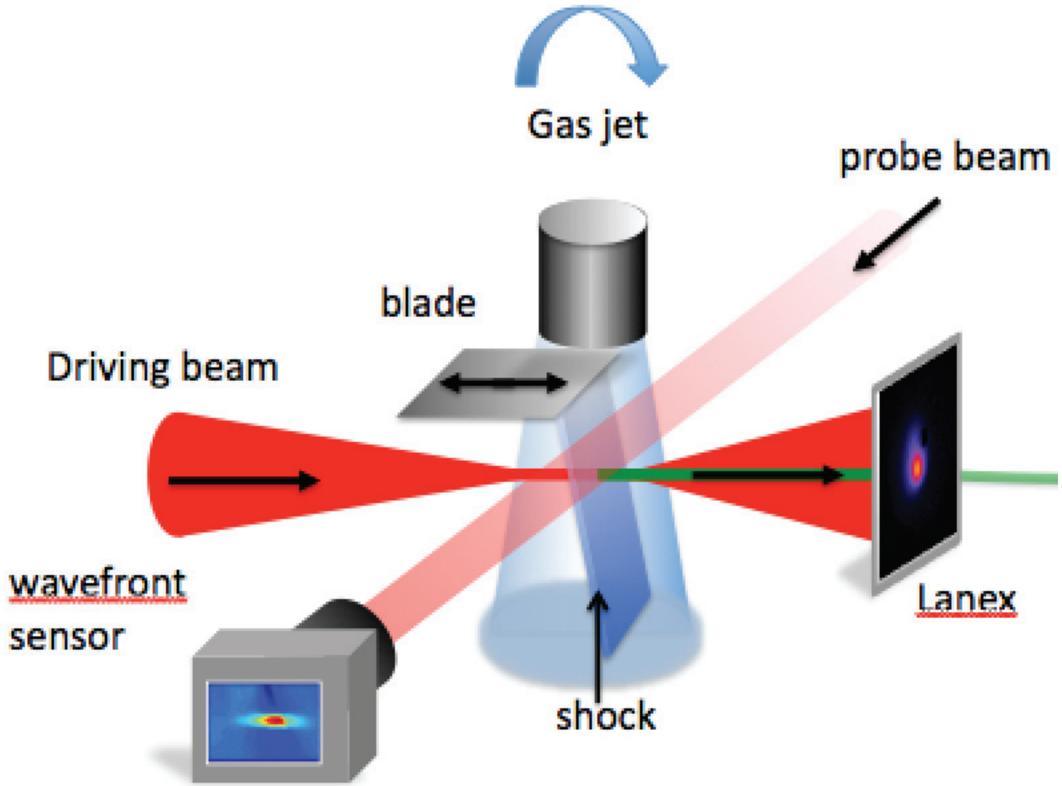


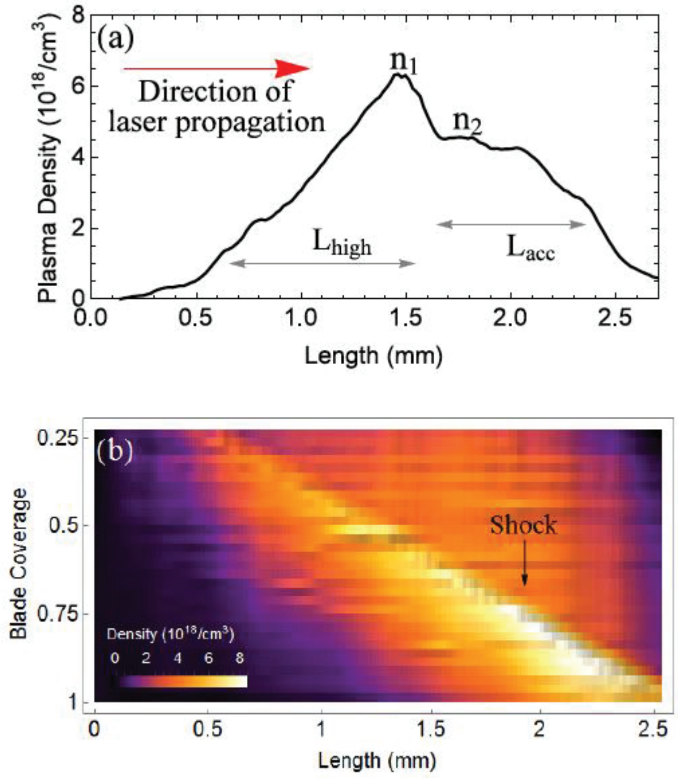

With VISA 275 MeV→ $\lambda_l$=50 nm

- Further enhancements with tapered undulator, seeding possible

# Jet-blade LPA developed:
# Localized injection at sharp density down ramp

Swanson *et al*. PR-AB 20, 051301 (2017)




Down ramp injection:

Bulanov, S, et al., *PRE* (1998), Suk, H., et al., PRL (2001), Geddes, C.G.R. et al., *PRL* (2008), Gonsalves, A.J. et al., *Nature* (2011)

# Tilted jet-blade LPA: circular beams without pointing kick

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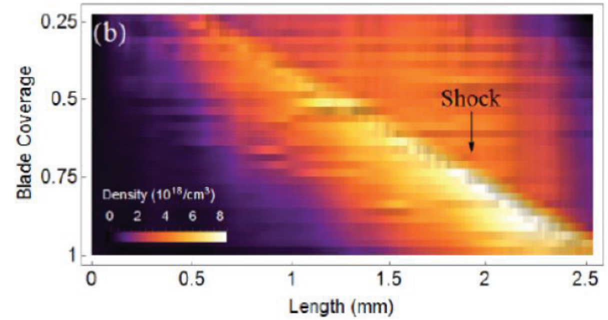


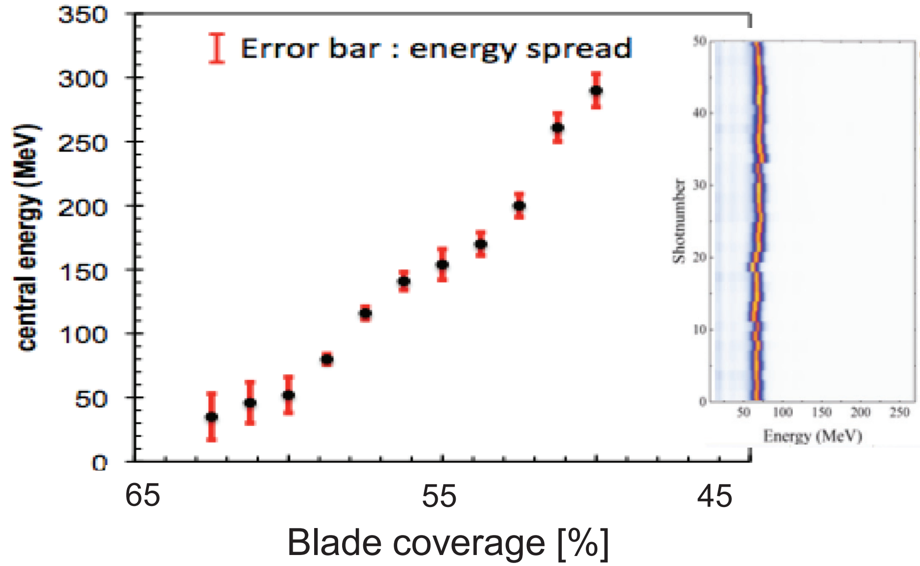

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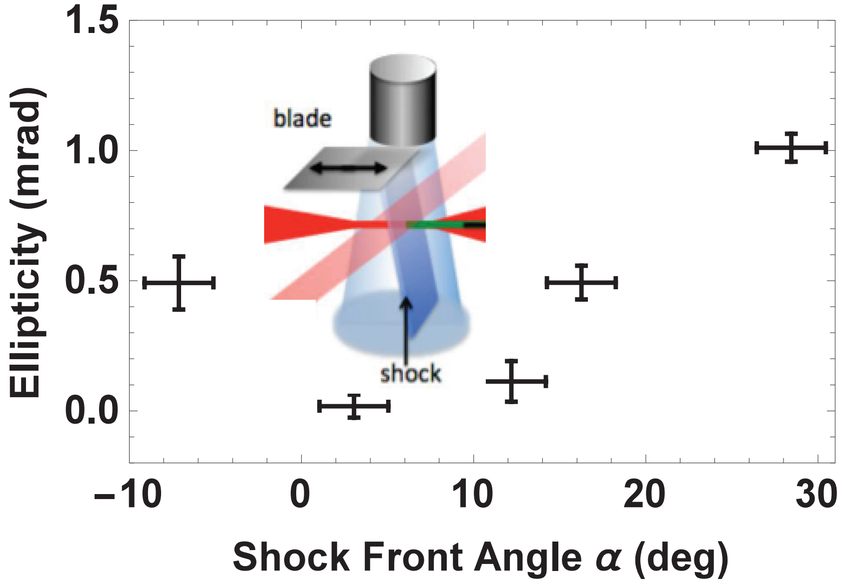


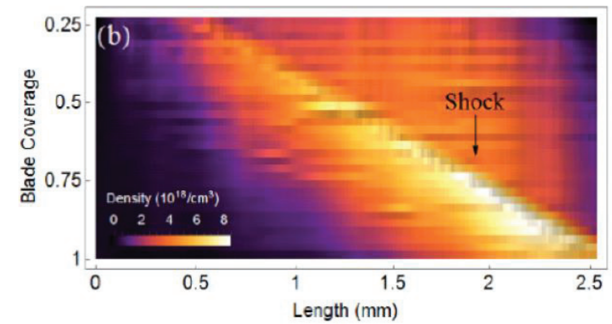


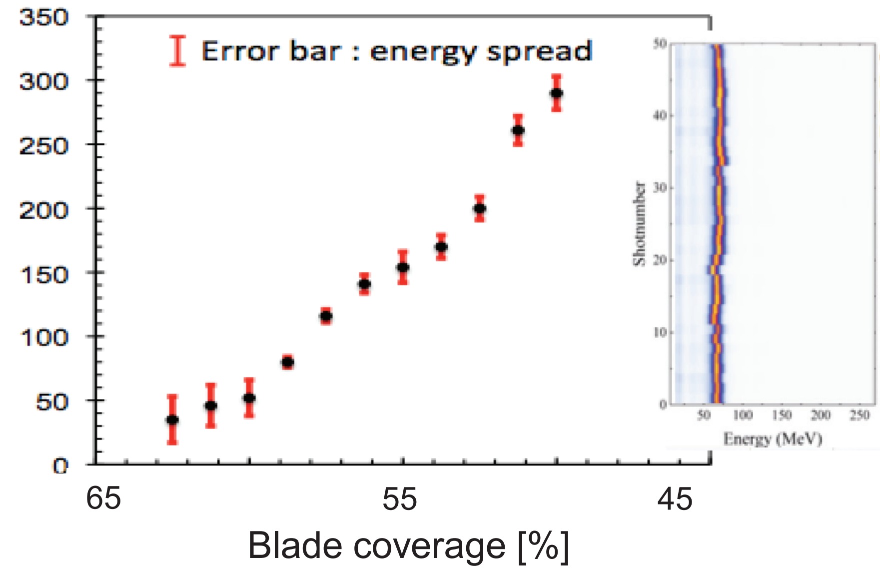

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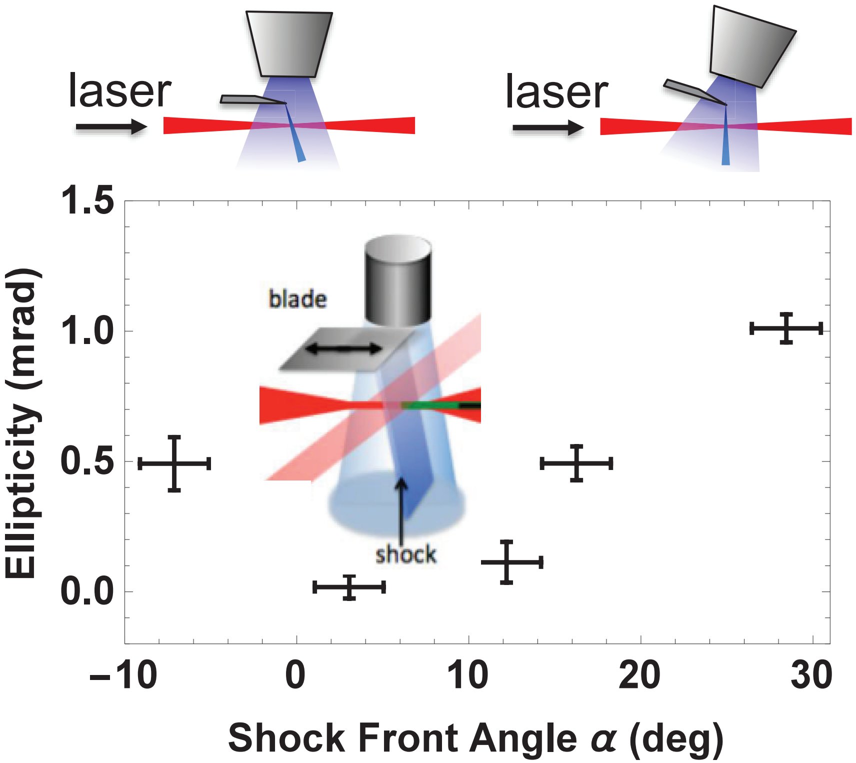


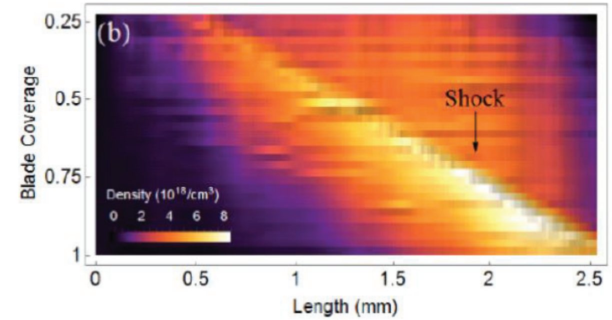


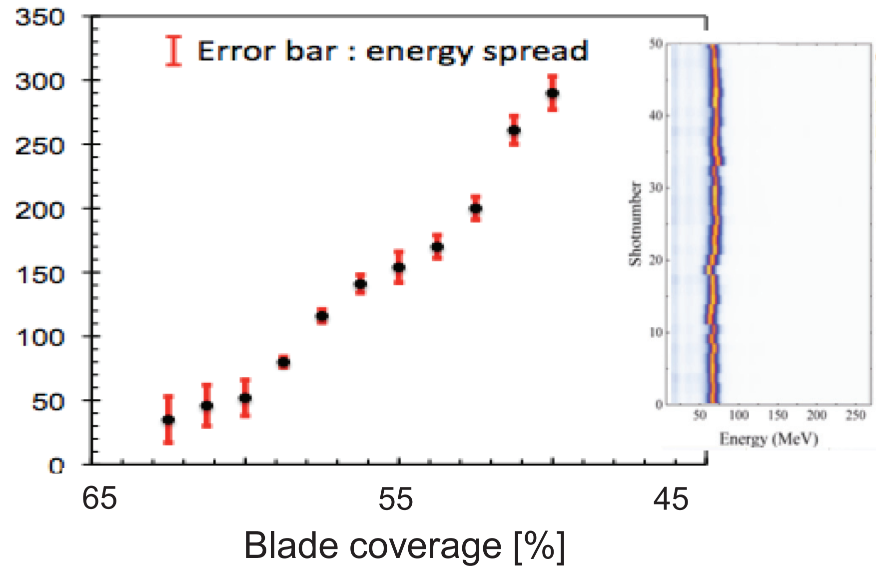

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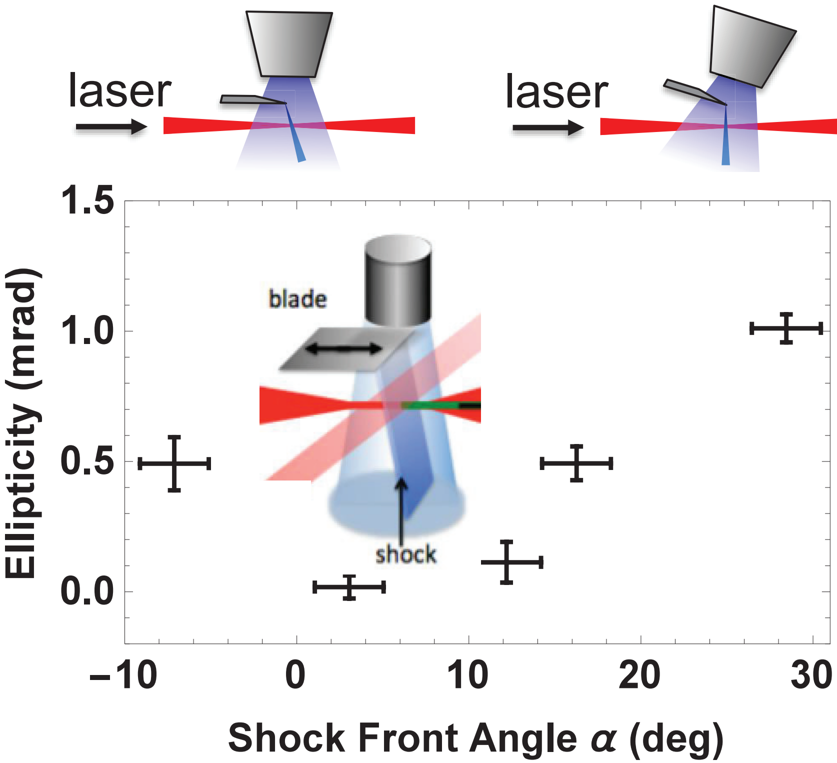
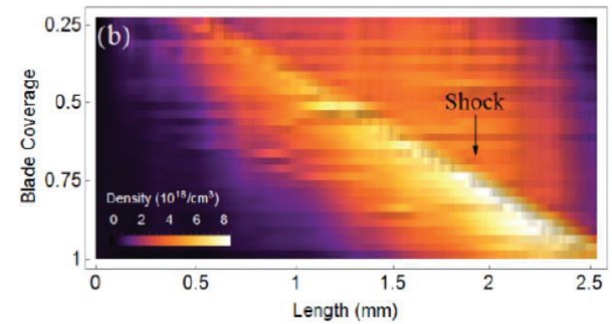
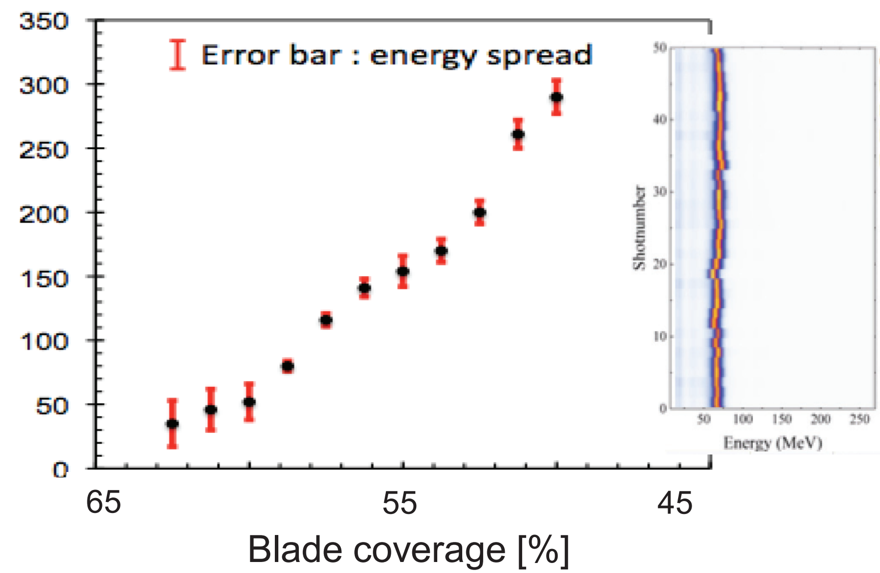
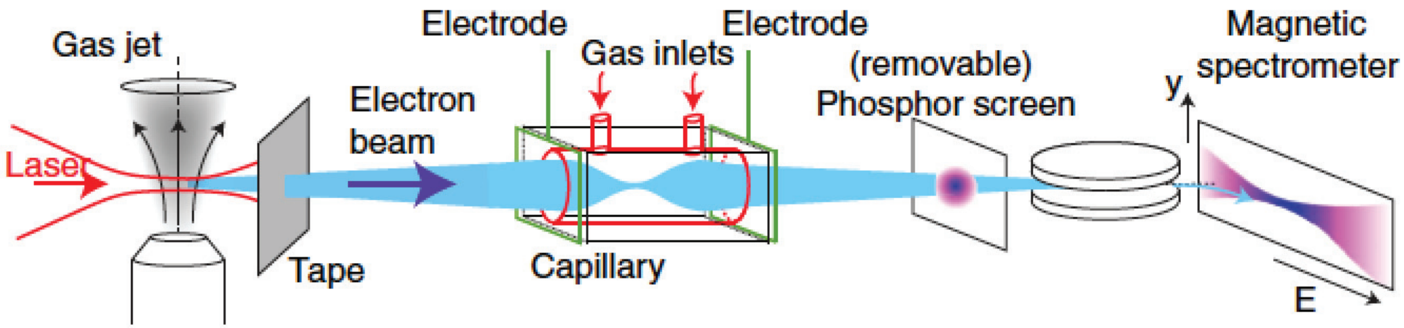


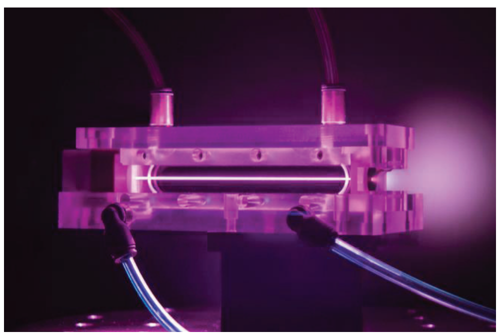



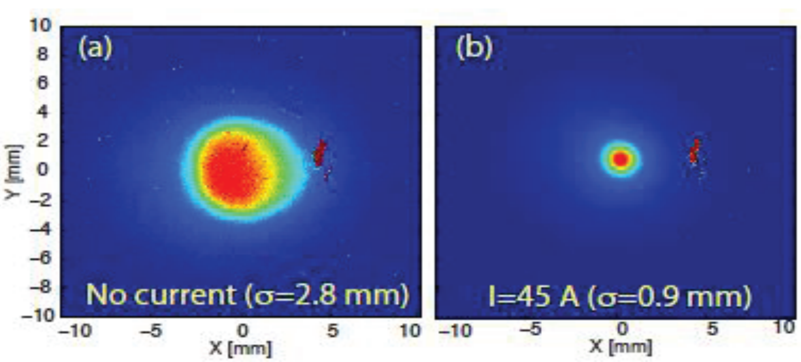

- Down-ramp provides controlled injection
- Tunable & stable
- Tilted jet and extensive plasma characterization → optimum performance
- 10-50 pC, 2-6% dE/E, 50 to >200 MeV

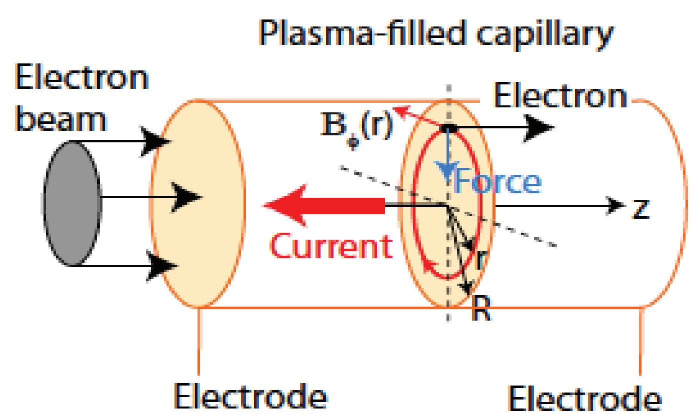
# Active plasma lenses developed at LBNL, great potential for compact applications



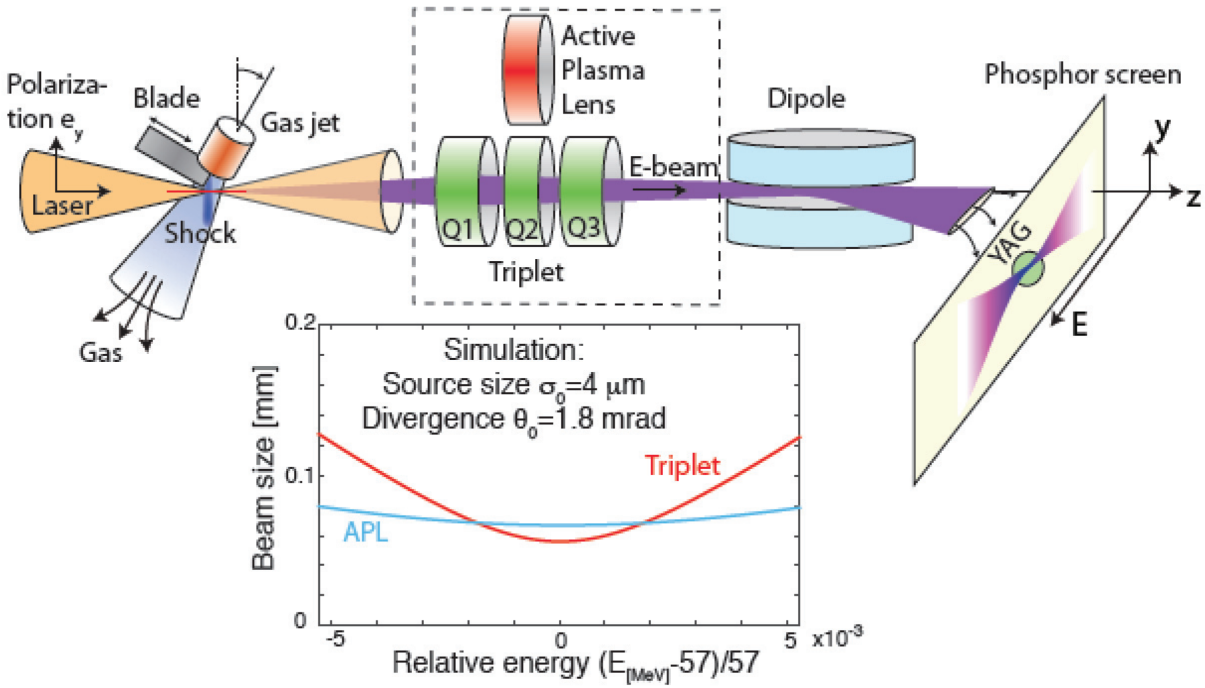
2015: LBNL re-developed active plasma lens
• Radial-symmetric
• Tunable with discharge current
• Strong gradients multi-kT/m (<10 cm-scale focal lengths for GeV beams)
• Now also at DESY, Frascati, CERN, Rutherford




Panofski *et al*. RSI 1950
van Tilborg *et al*. PRL **115**, 184802 (2015)

# APL radial symmetry & short focal length enhance the energy bandwidth of the transport system




Migliorati *et al.* PRSTAB 2013, Loulergue *et al.* New. J. Phys. 2015

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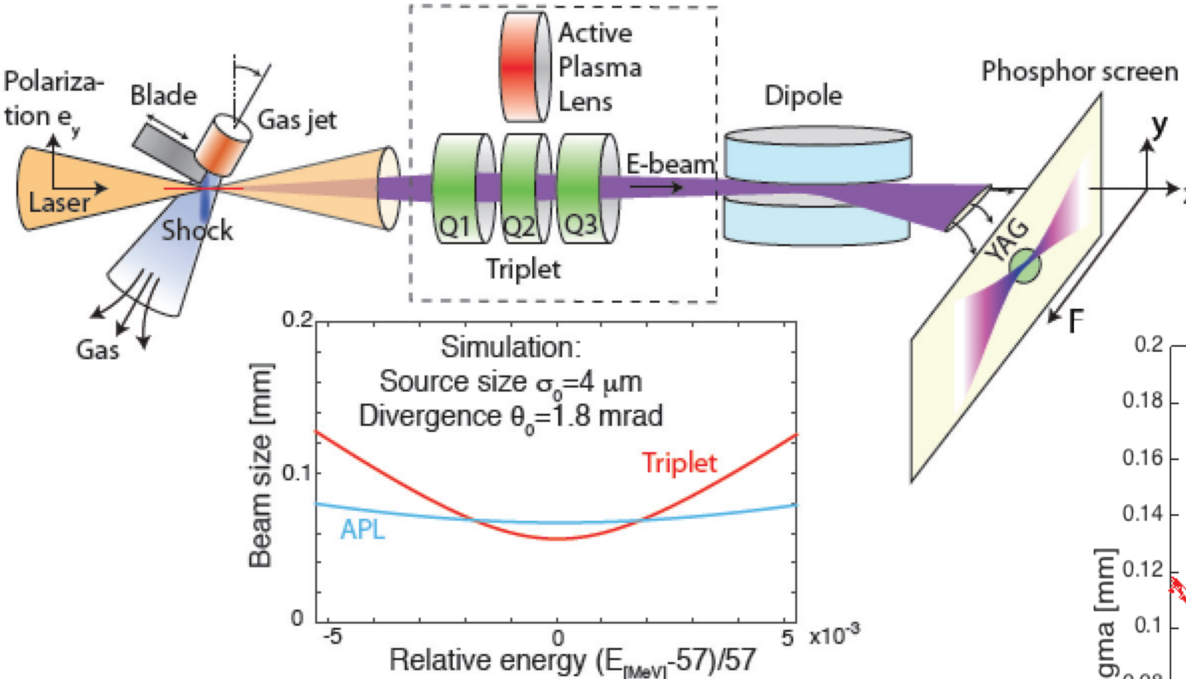


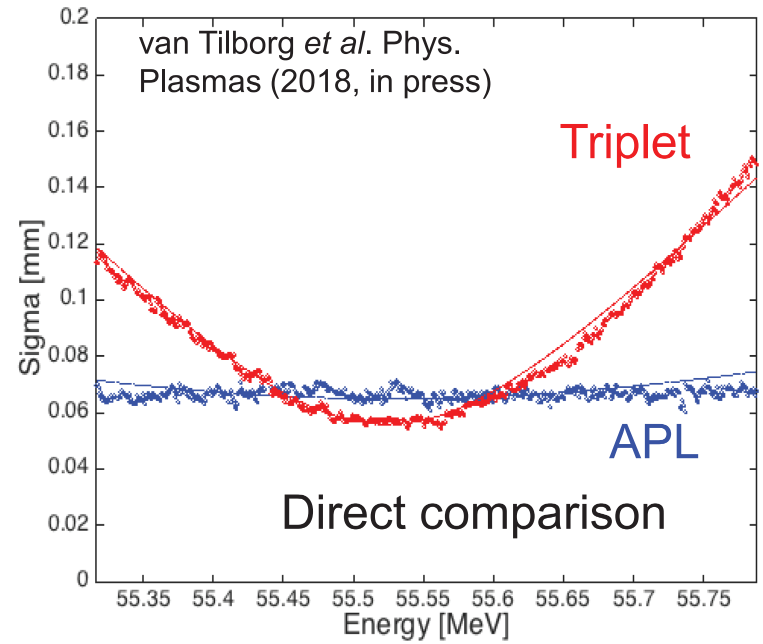


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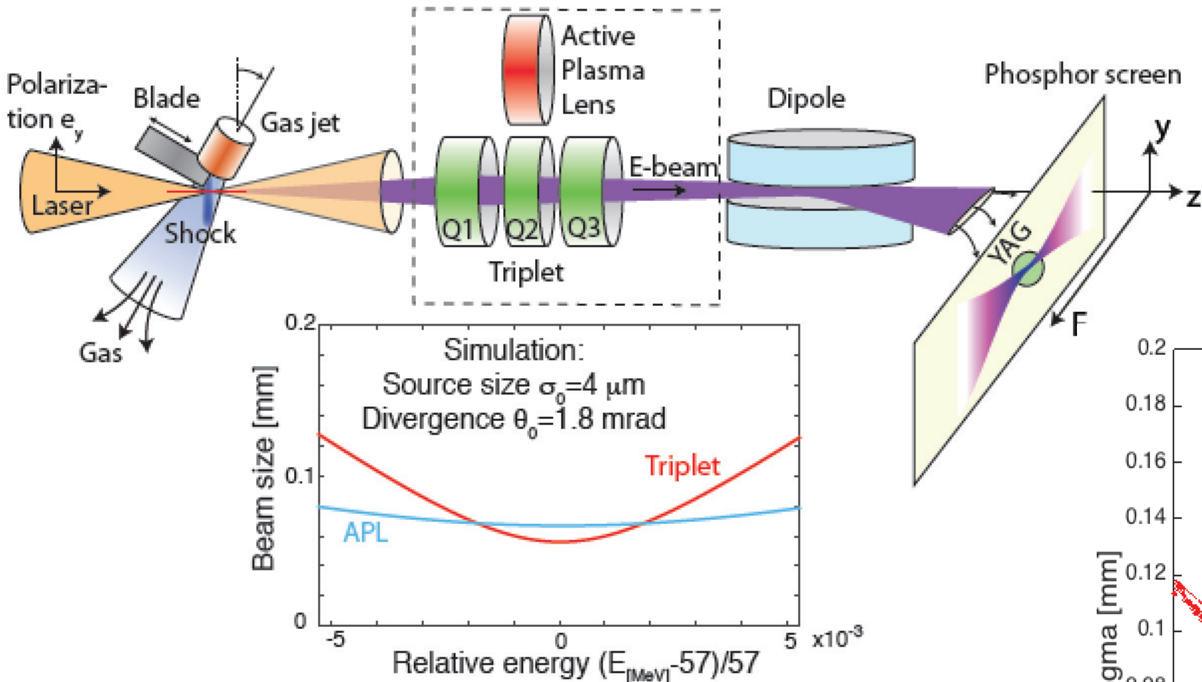
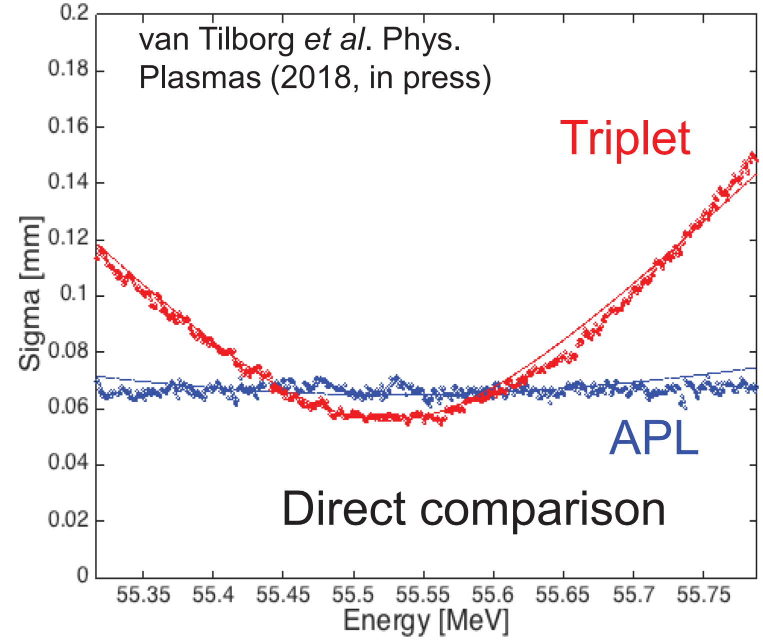


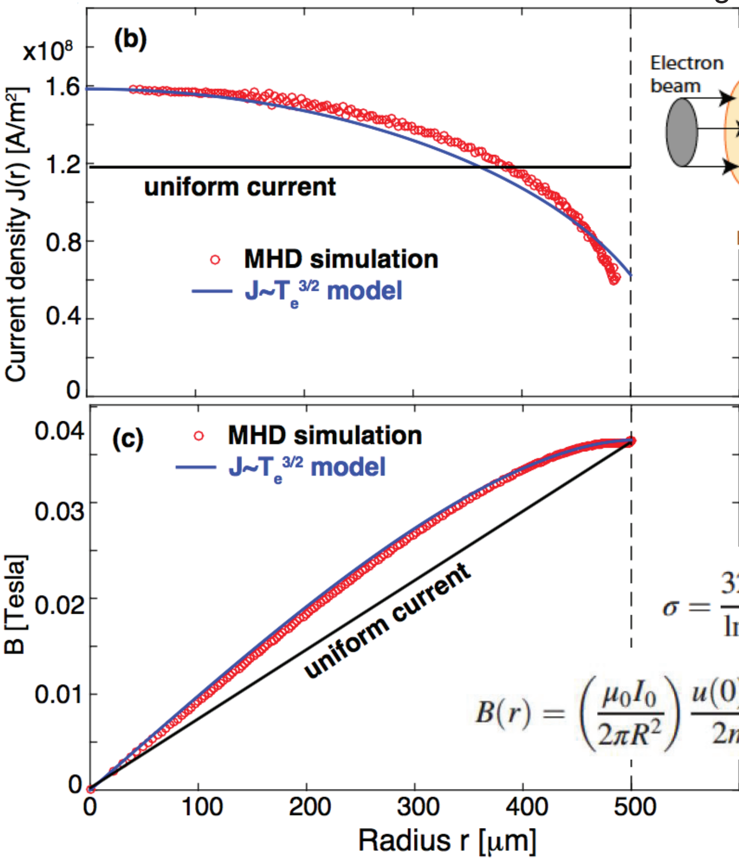

Weak chromaticity
- More forgiving for source energy fluctuations
- Slippage → photons remain overlapped with e-beam

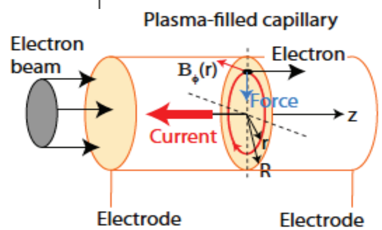
Strong focusing
- Divergence is reduced closed to source (less emittance growth, less bunch lengthening)

Migliorati *et al.* PRSTAB 2013, Loulergue *et al.* New. J. Phys. 2015

# Understanding of discharge current distribution critical to lens quality: linear regime possible

van Tilborg *et al*. PR-AB 20, 032803 (2017)




$$\sigma = \frac{32\epsilon_0^2}{\ln\Lambda}\frac{(k_B T_e)^{3/2}}{e^2 m_e^{1/2}}$$

$$B(r) = \left(\frac{\mu_0 I_0}{2\pi R^2}\right)\frac{u(0)^{3/7}}{2m_I}x\left[1 - \frac{3x^2}{56u(0)^{4/7}}\right]$$

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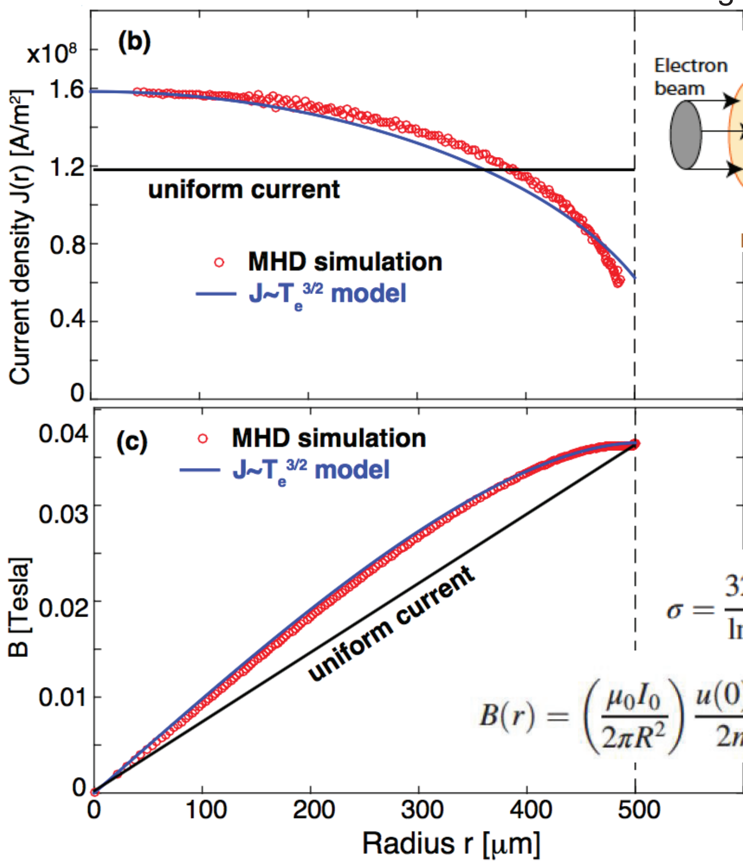


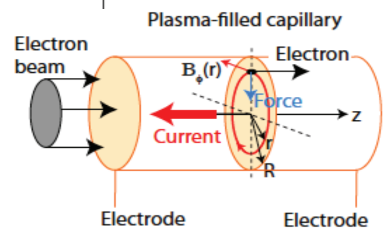


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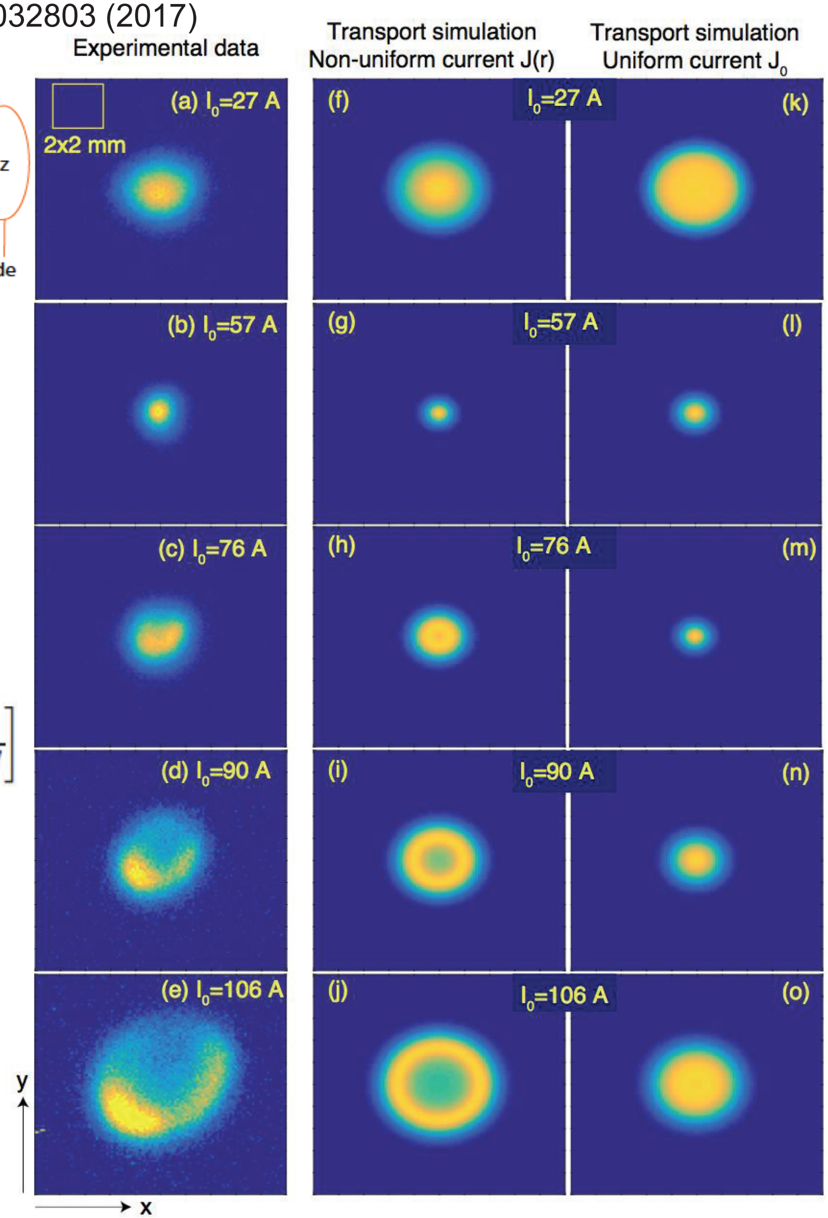

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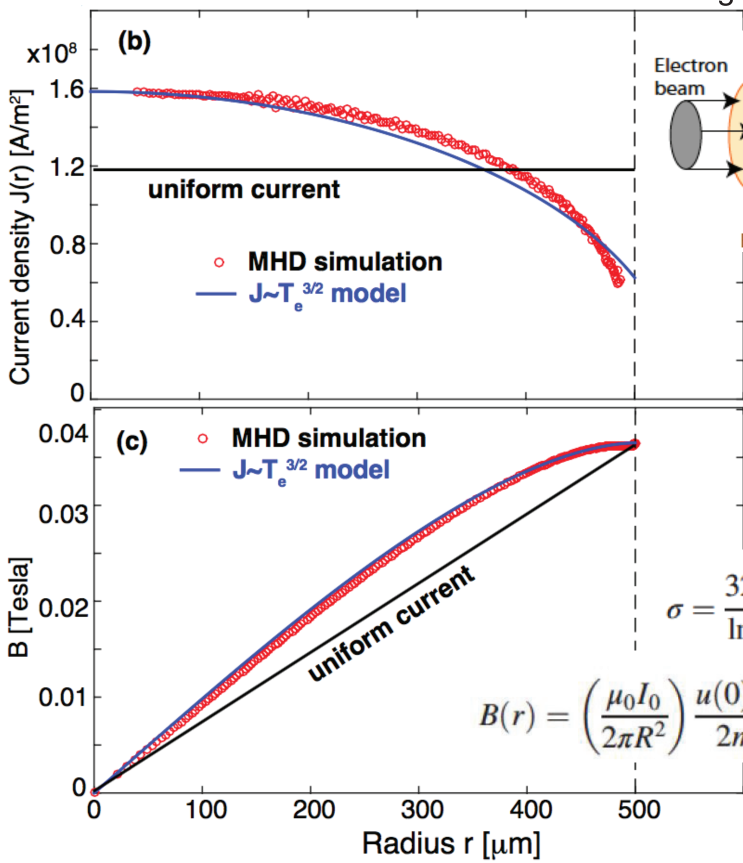
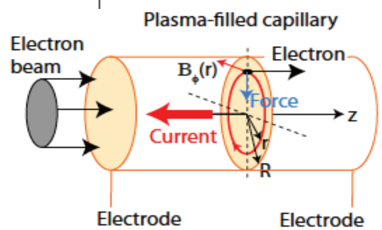
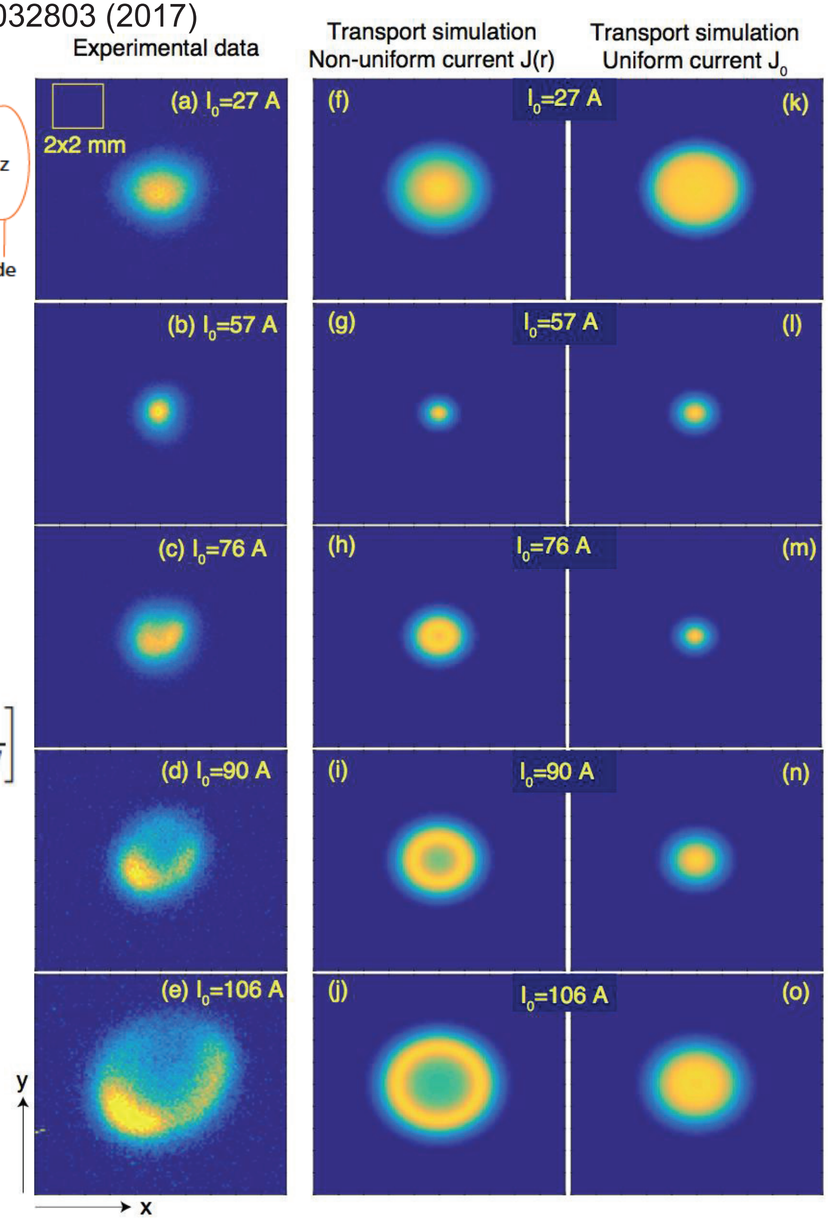



$$\sigma = \frac{32\epsilon_0^2}{\ln \Lambda}\frac{(k_B T_e)^{3/2}}{e^2 m_e^{1/2}}$$

$$B(r) = \left(\frac{\mu_0 I_0}{2\pi R^2}\right)\frac{u(0)^{3/7}}{2m_I}x\left[1 - \frac{3x^2}{56u(0)^{4/7}}\right]$$




- Studied analytically & experimentally (agreement)
- (also confirmed at Frascati: Pompili *et al.* APL 2017)
- Relevant consequence is loss of focused beam density
- Can be mitigated for FWHM < $R_{APL}/2$
- But if too dense: beam-driven wakefields [Lindstrom PRAB (2018), van Tilborg Phys. Plasmas (2018, in press)]
- Short e-beam duration mitigates wakefield deterioration

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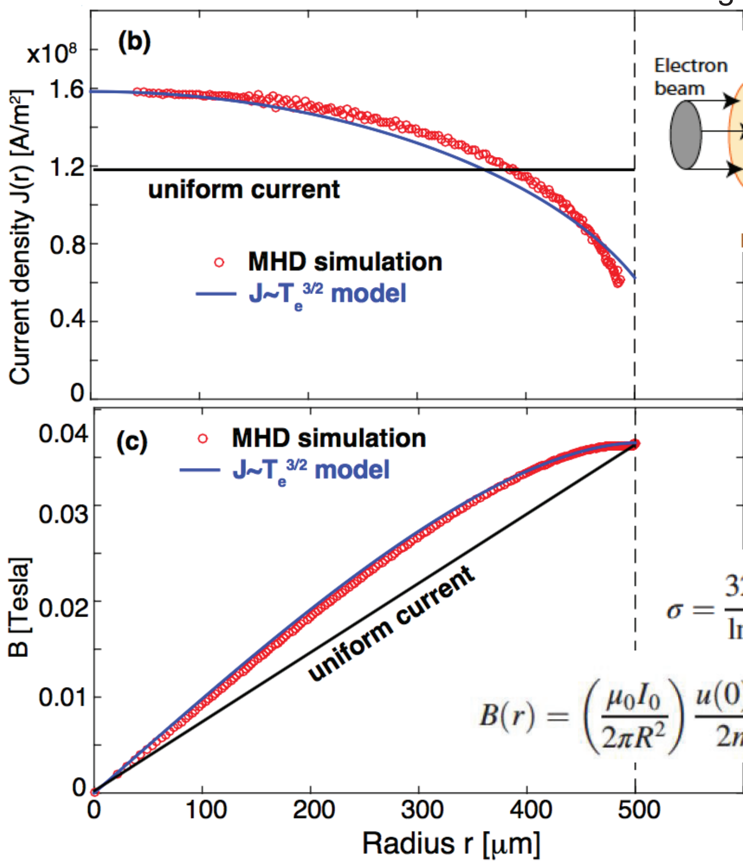


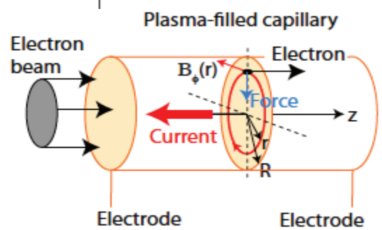


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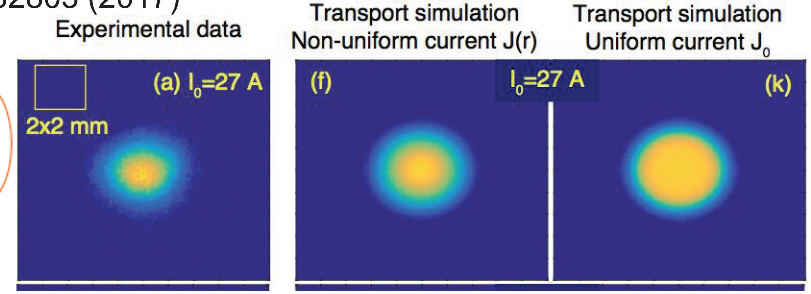


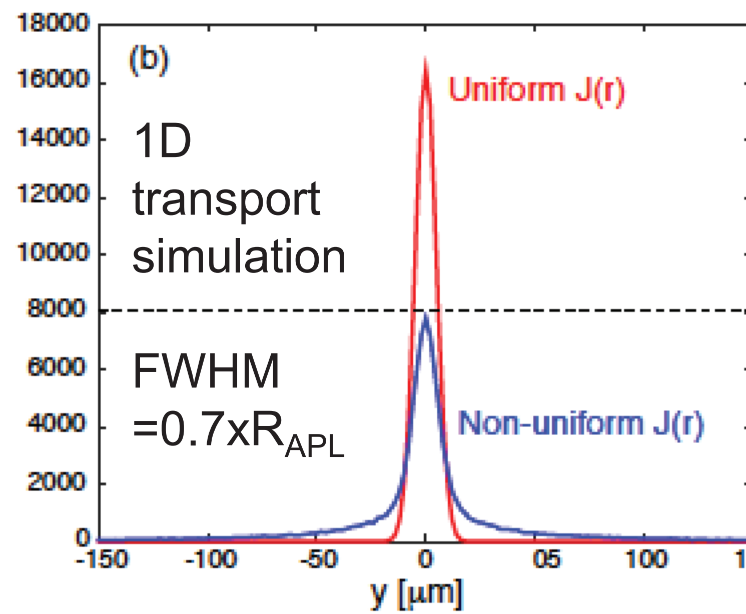


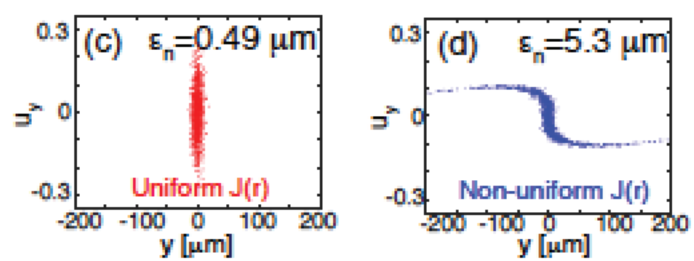


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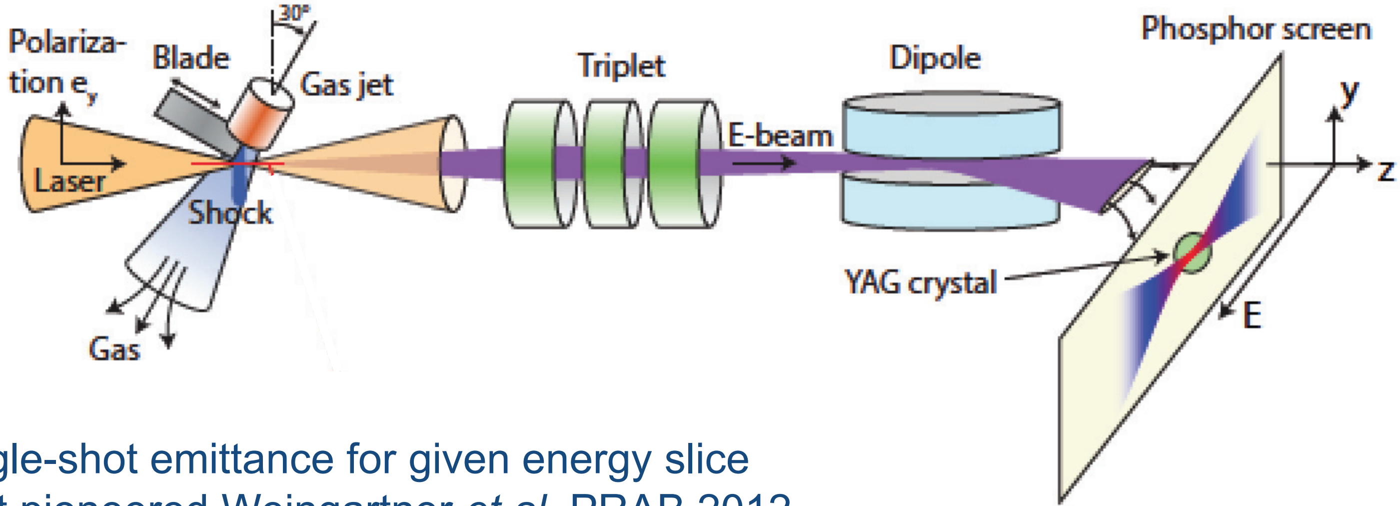
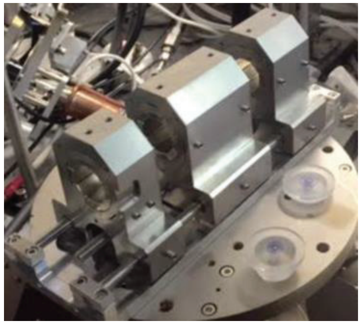
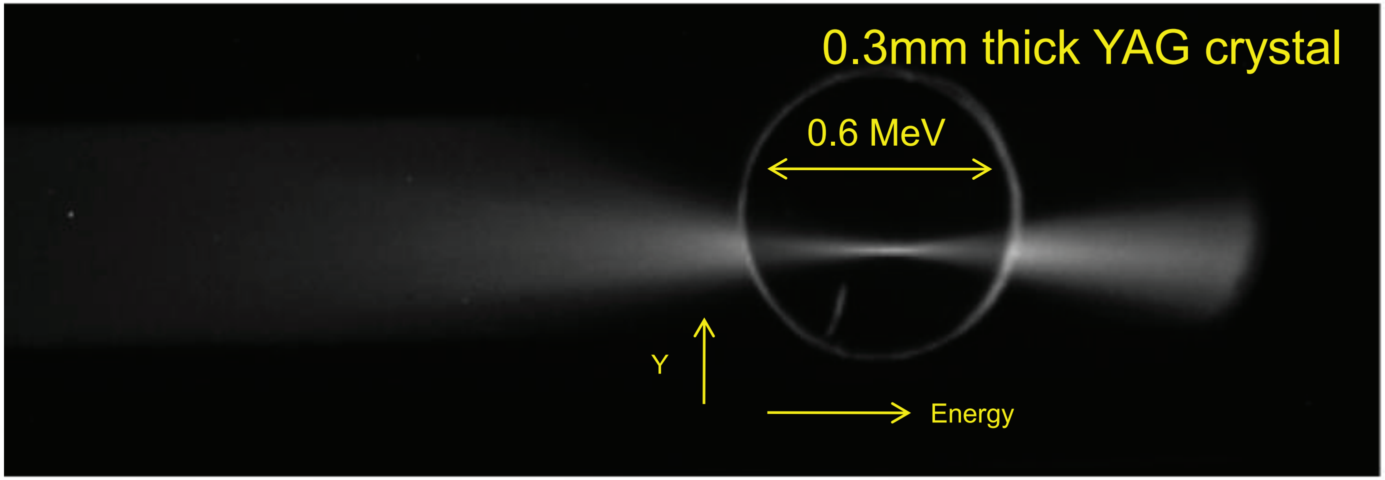
# Developed high-resolution setup to measure single-shot energy-resolved emittance




RadiaBeam triplet



- Single-shot emittance for given energy slice
- First pioneered Weingartner *et al.* PRAB 2012
- Optimized spatial/energy resolution & stability → LPA parameter scans
- Compare measured $\sigma_y(E)$ to transport simulations source-to-screen
- Higher-order transport model was used: $1^{st}$-order approximation was found to be adequate



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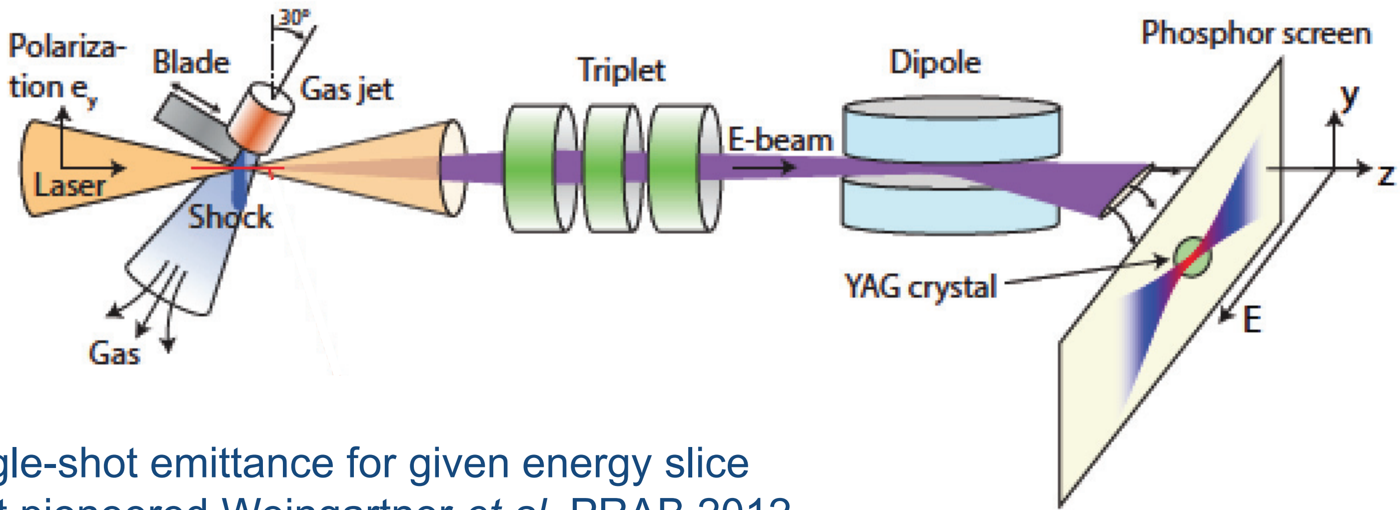


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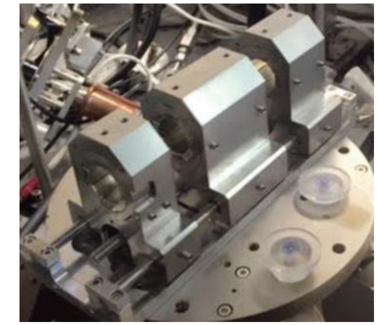

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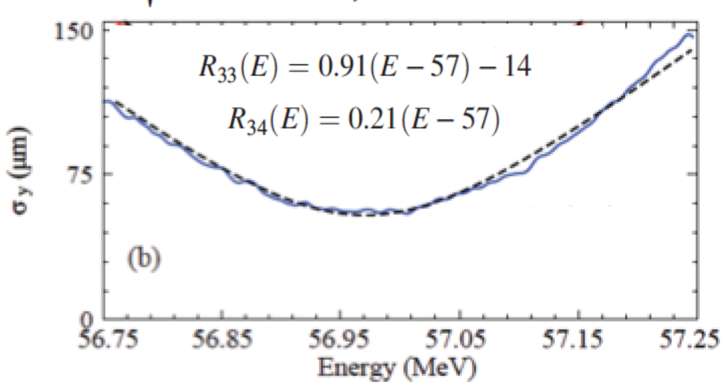
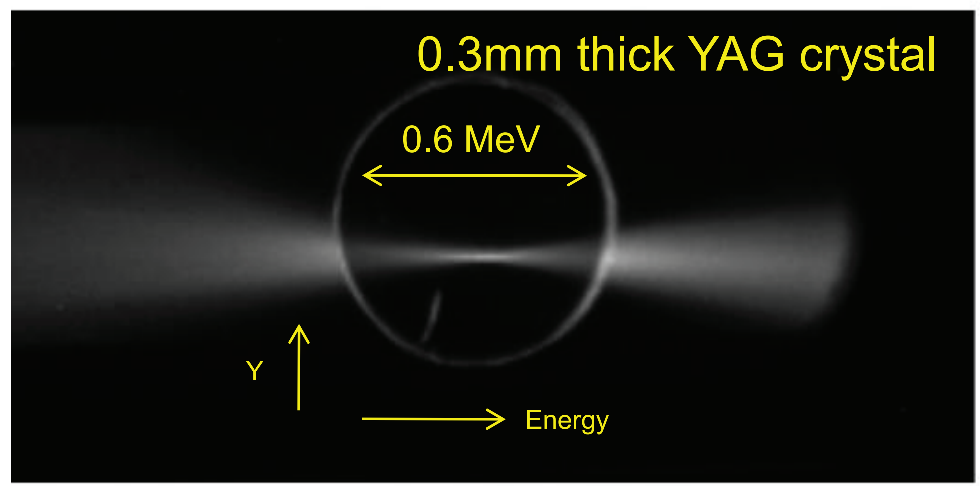
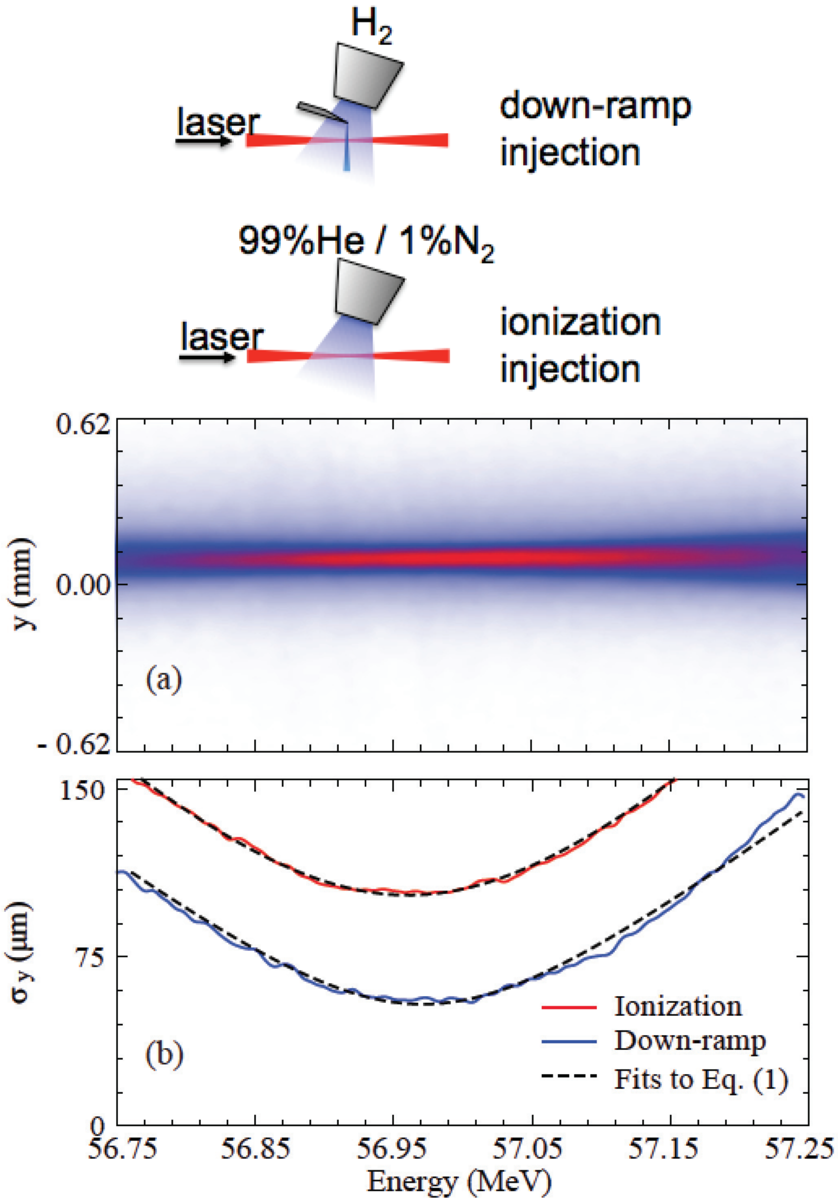
$$\sigma_y(E) = \sqrt{[R_{34}(E^*)]^2\left(\frac{\epsilon_y}{\gamma\sigma_{y0}}\right)^2 + [R_{33}(E^*)]^2\sigma_{y0}^2}, \qquad (1)$$



# First direct observation of emittance dependence on injection mechanism




Barber *et al.* Phys. Rev. Lett. 119, 104801 (2017)

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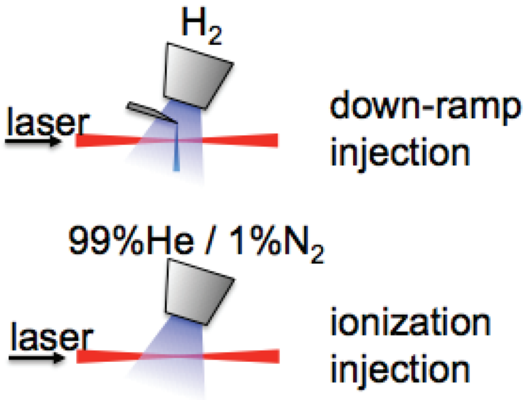


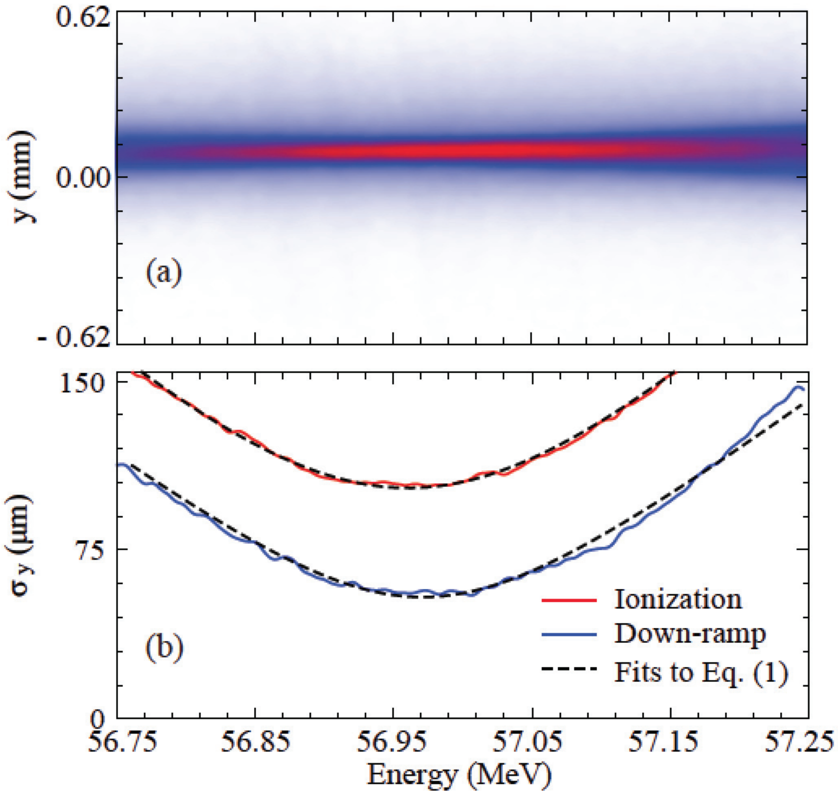


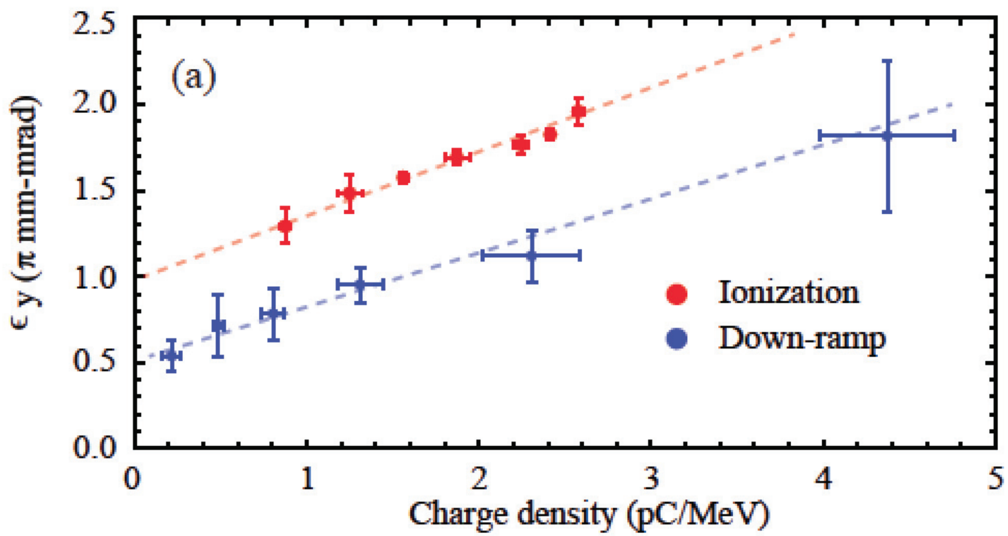


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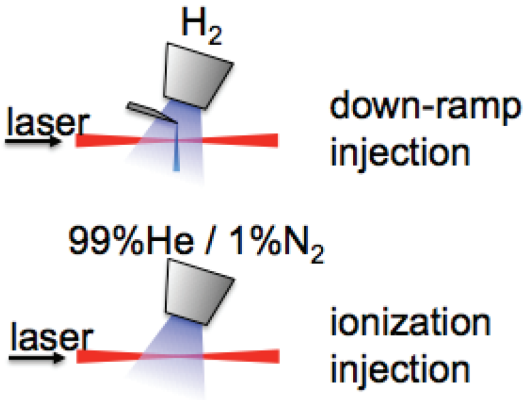
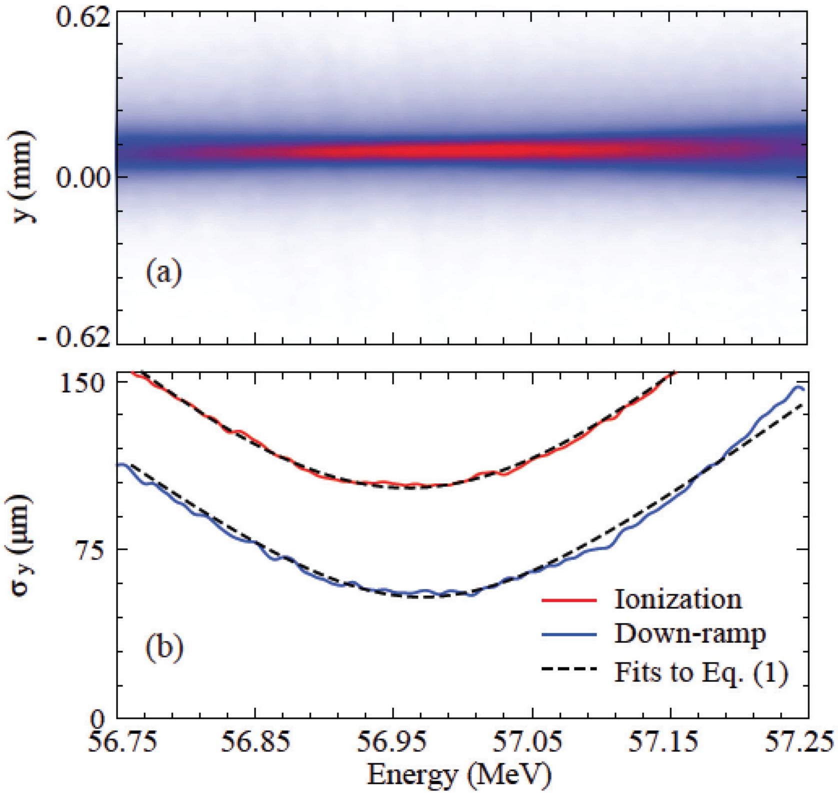
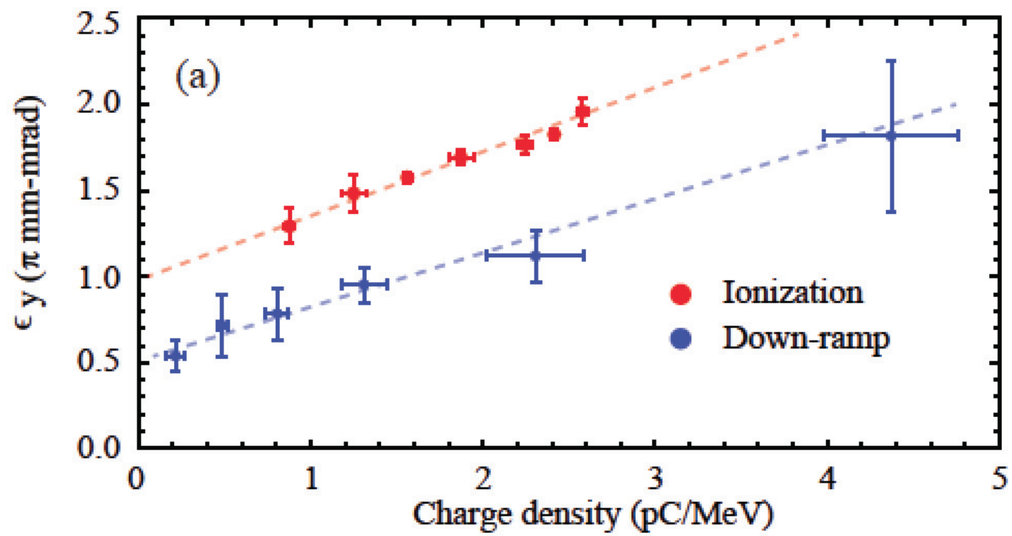



- Similar e-beams, two injection mechanisms
- Down ramp injection best at $\varepsilon_n$<1 μm (at 2 pC/MeV)
- Space charge over 2.7m plays (partial) role
- Confirmed by simulations
- First-of-kind data in LPA community (stability)
- Diagnostic and sub-μm demonstration critical to FEL and other applications

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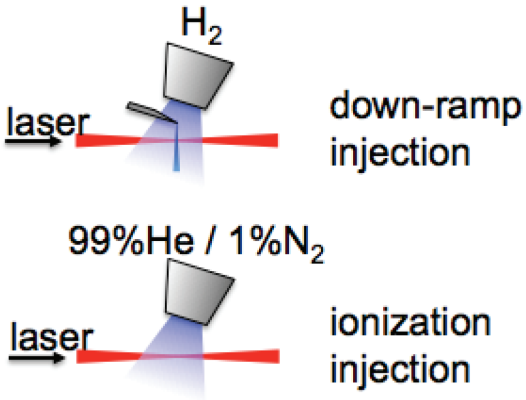


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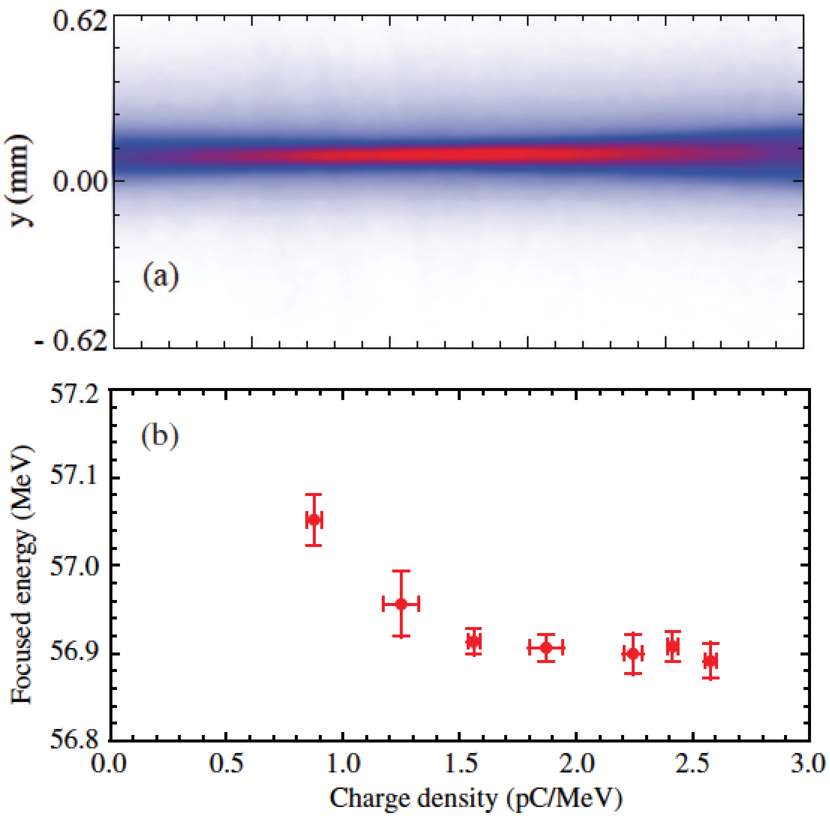


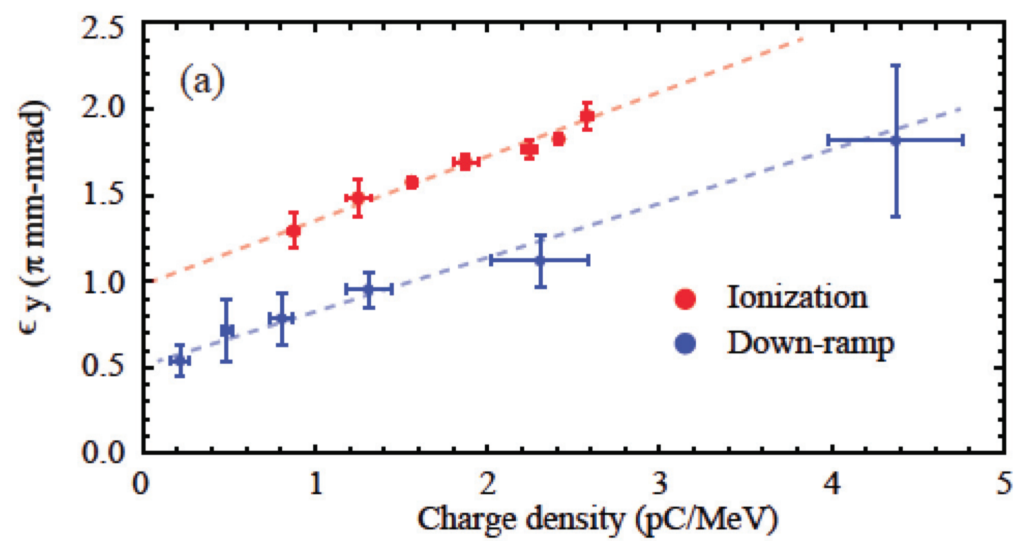


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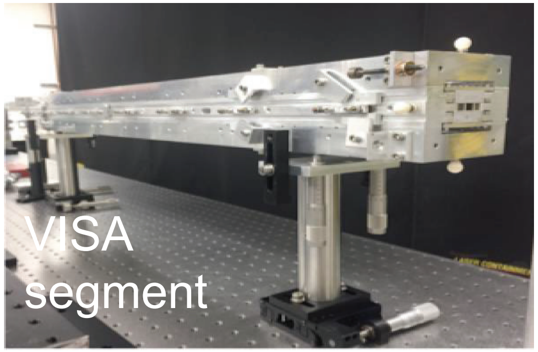
# Assembled state-of-the-art magnet test bench for VISA undulator using pulsed wire method (UCLA/Brookhaven collaboration)

VISA undulator Carr *et al.* PRSTAB **4**, 122402 (2001)

4 FODO cells per section. 4 one-meter sections

| Parameter | Symbol | Value |
|---|---|---|
| Undulator period | $\lambda_w$ | 1.8 cm |
| Undulator length | $L$ | 4 m |
| Undulator Parameter | $K$ ($\bar{K}$) | 1.26 (0.89) |



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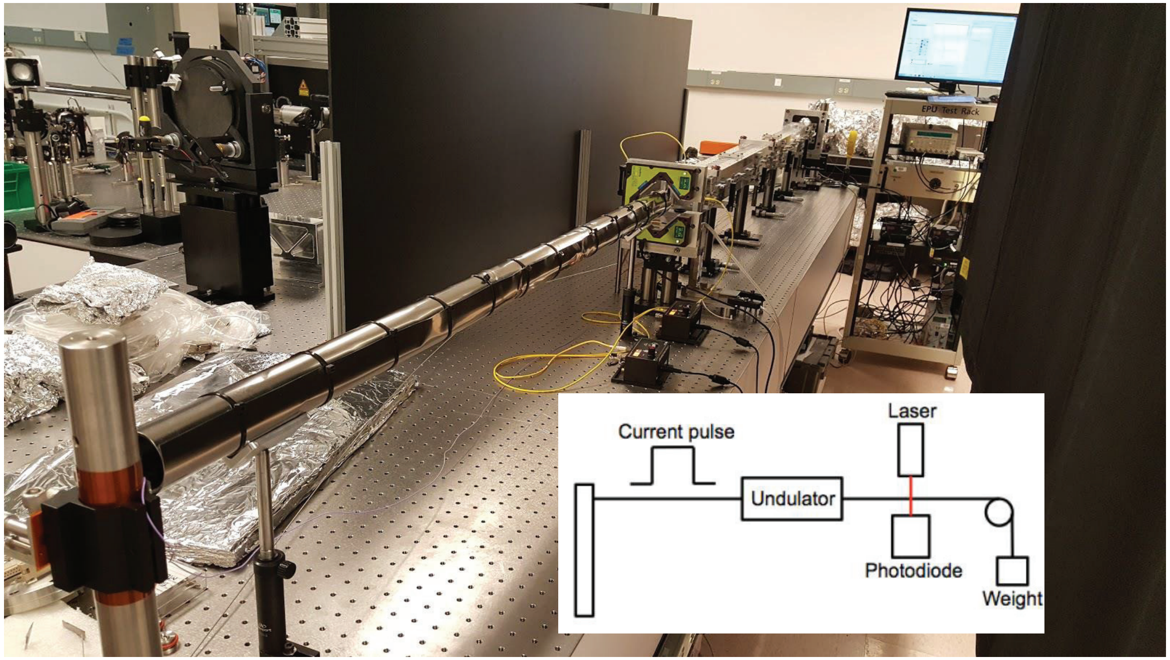
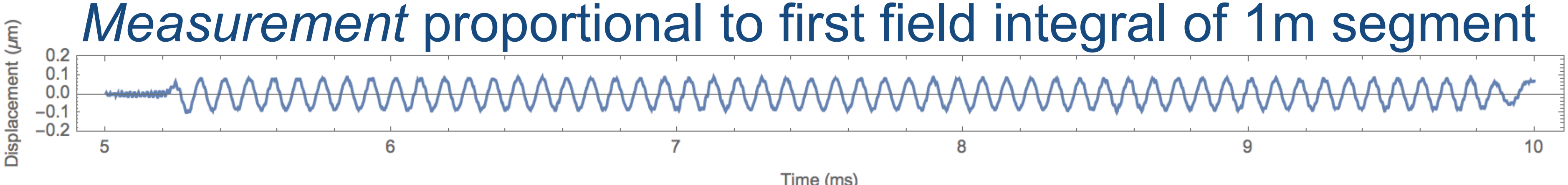



## *Measurement* proportional to first field integral of 1m segment

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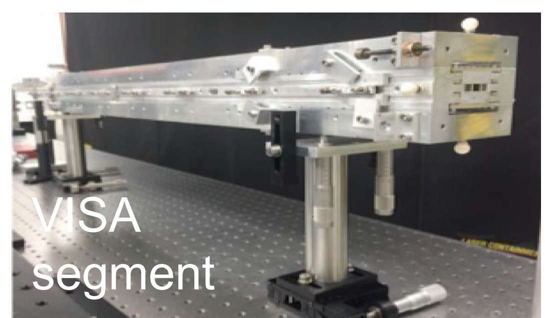

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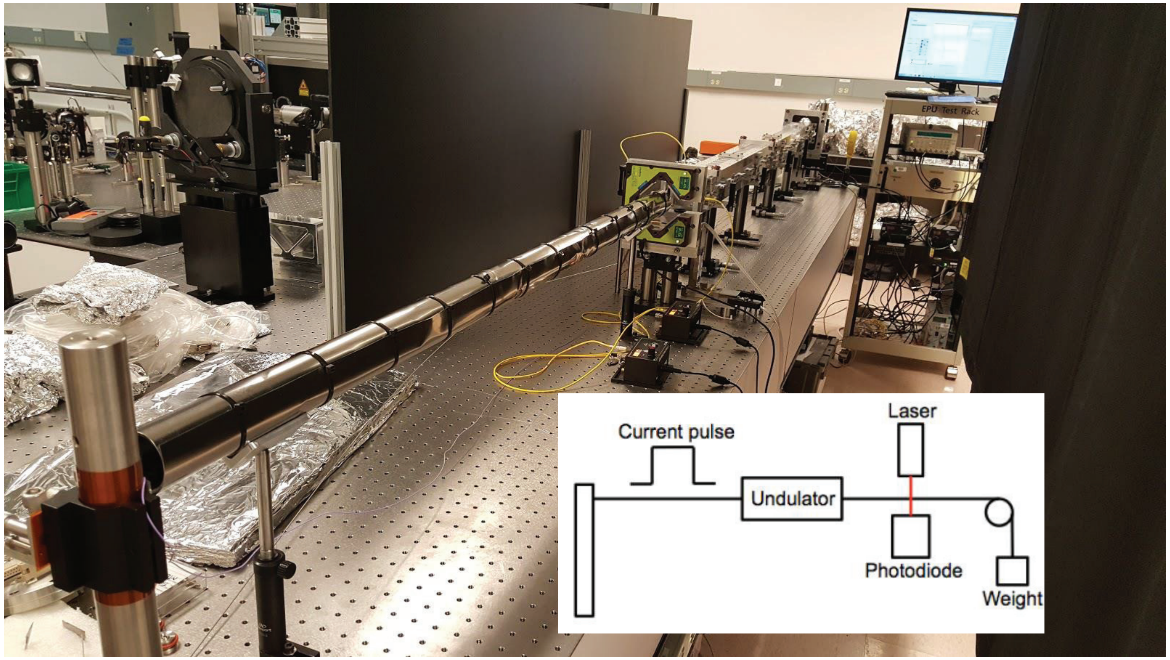


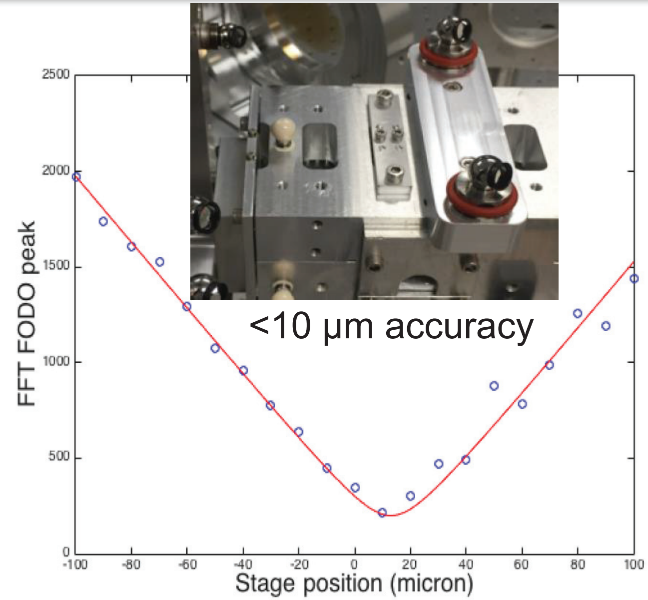


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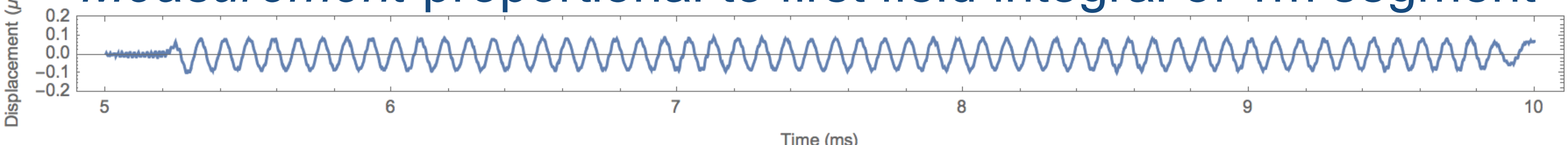


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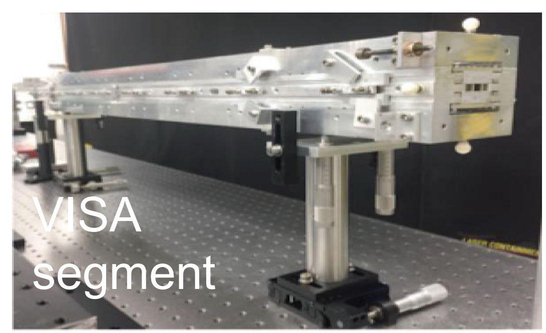
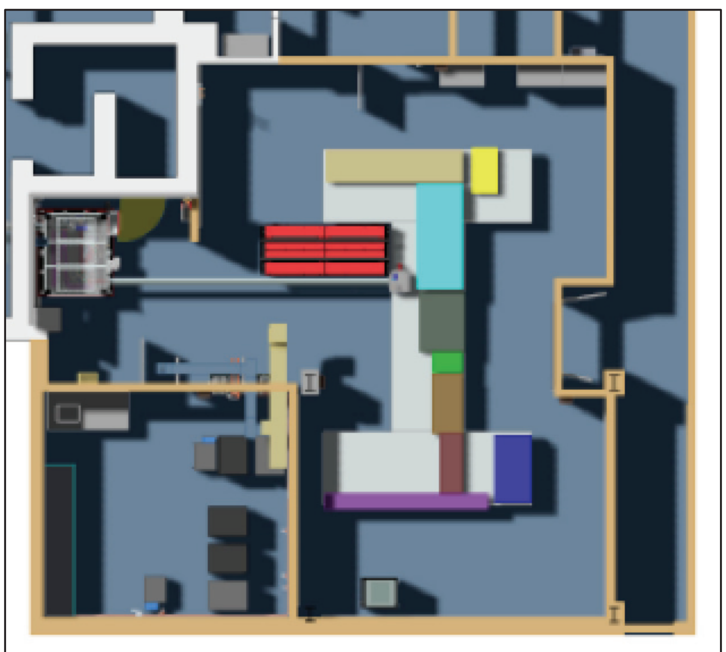


# FEL-dedicated single-table laser system developed
# Radiation caves being re-commissioned



100 TW laser system

- mJ-level front-end: COHERENT
- multi-J amplifier: home-built
- Single GAIA pump (THALES)

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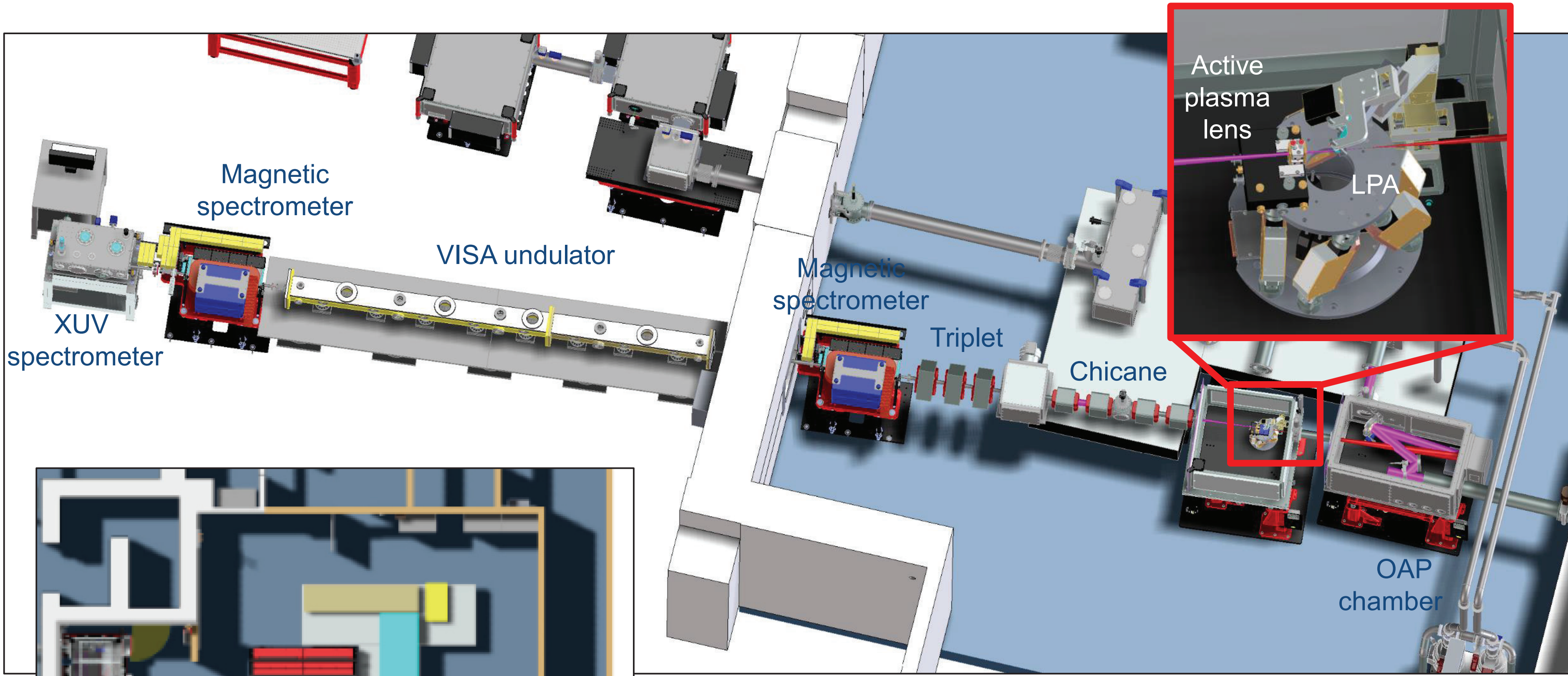


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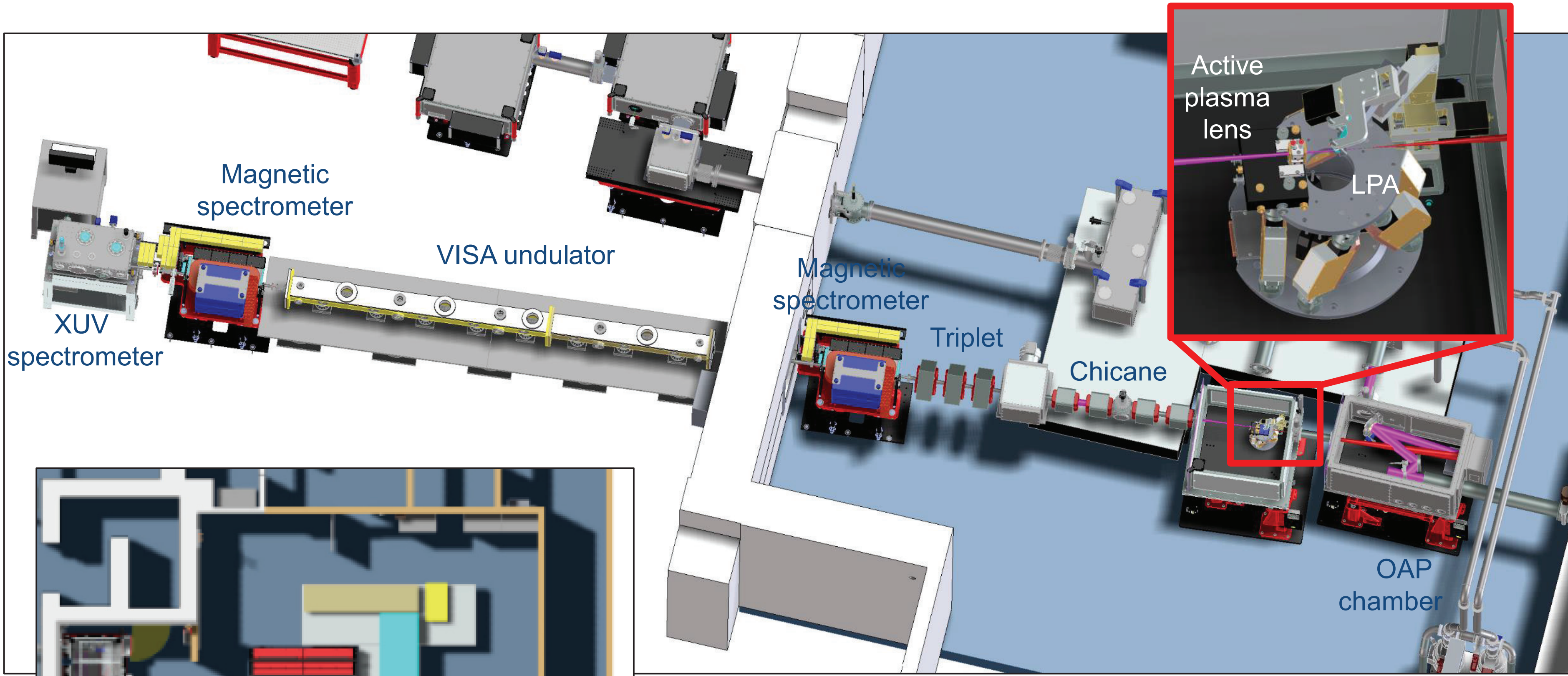
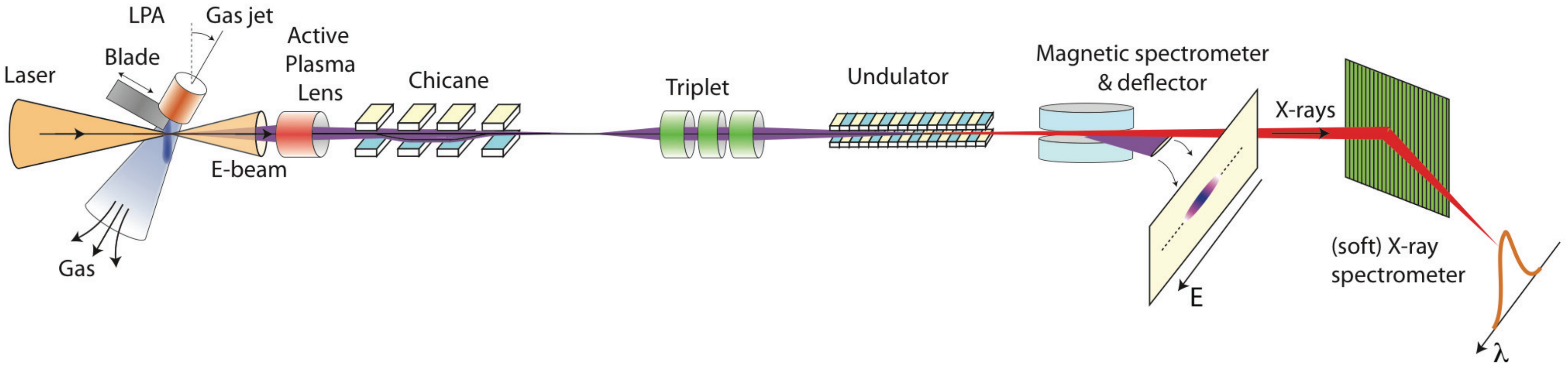



LPA & transport on-line in spring/summer 2018

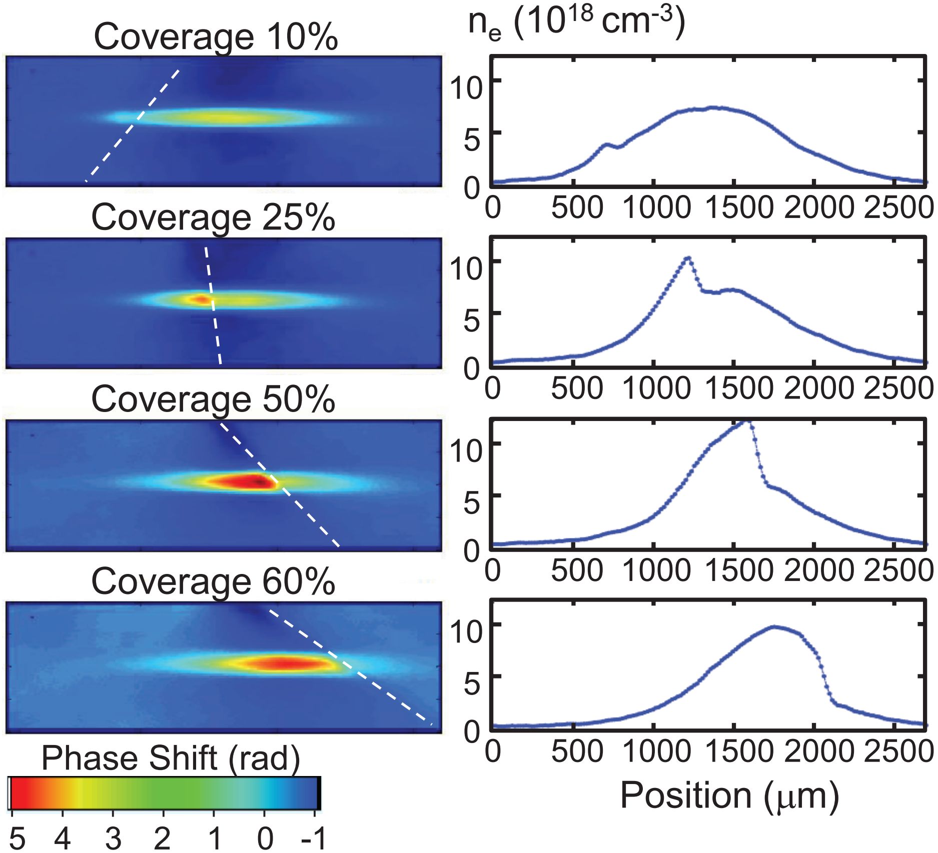
100 TW laser system
- mJ-level front-end: COHERENT
- multi-J amplifier: home-built
- Single GAIA pump (THALES)

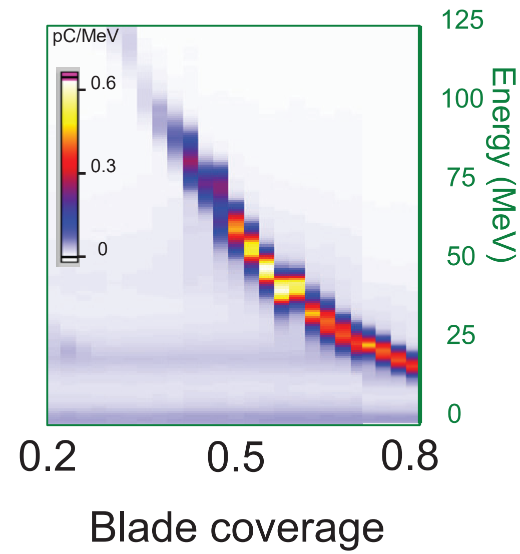
# Summary

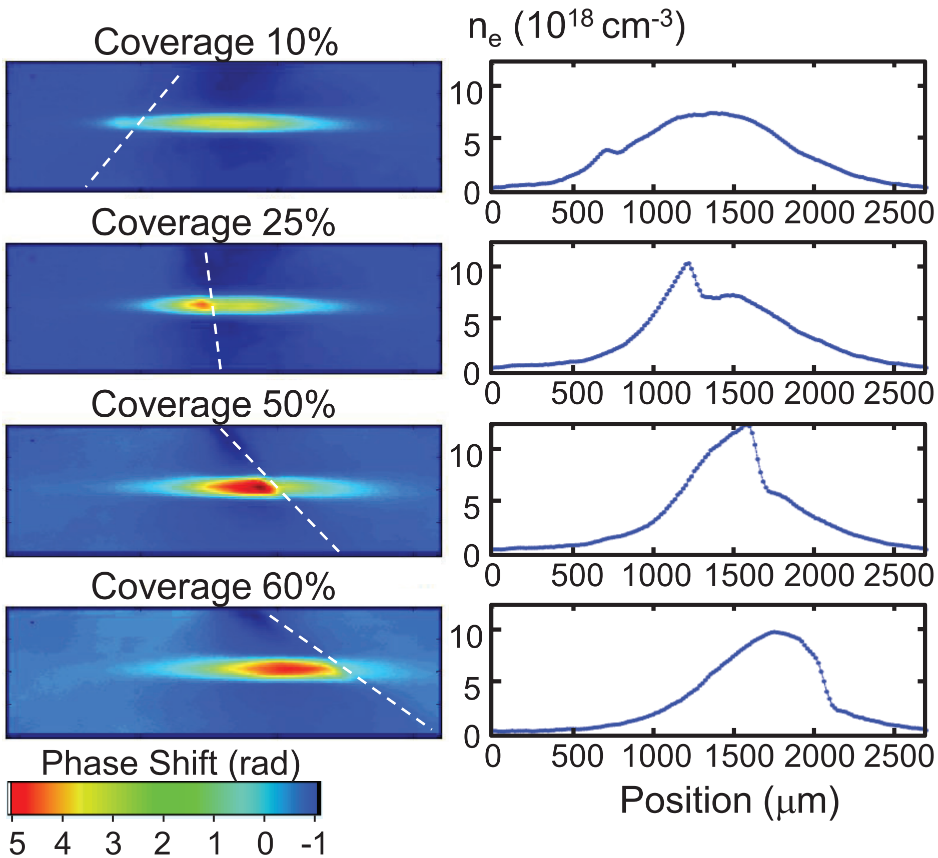
- Design and simulations completed for LPA FEL line
- Down-ramp jet–blade LPA developed: stable, tunable e-beams
- Active Plasma Lens offers advantages to FEL application
- First-of-kind LPA emittance parameter scans performed: down-ramp favorable to ionization injection
- VISA undulator being characterized & fiducialized section by section
- FEL-dedicated 100TW-driven LPA near completion



# the end


Coverage 10%
Coverage 25%
Coverage 50%
Coverage 60%
Phase Shift (rad)
5 4 3 2 1 0 -1
$n_e$ ($10^{18}$ $cm^{-3}$)
0 5 10
0 500 1000 1500 2000 2500
Position (μm)


pC/MeV
0.6
0.3
0
Energy (MeV)
125
100
75
50
25
0
0.2 0.5 0.8
Blade coverage


Coverage 10%
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5 4 3 2 1 0 -1
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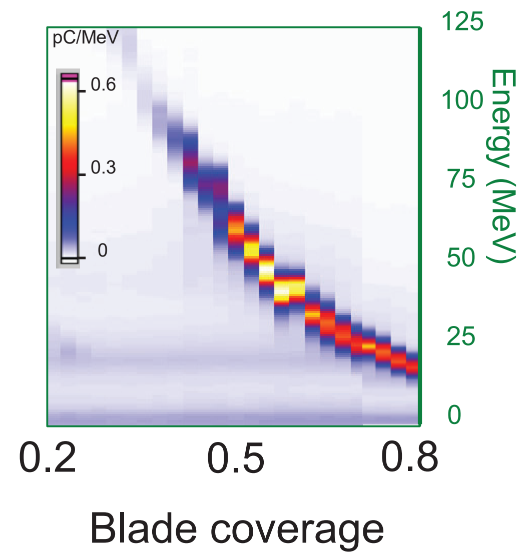
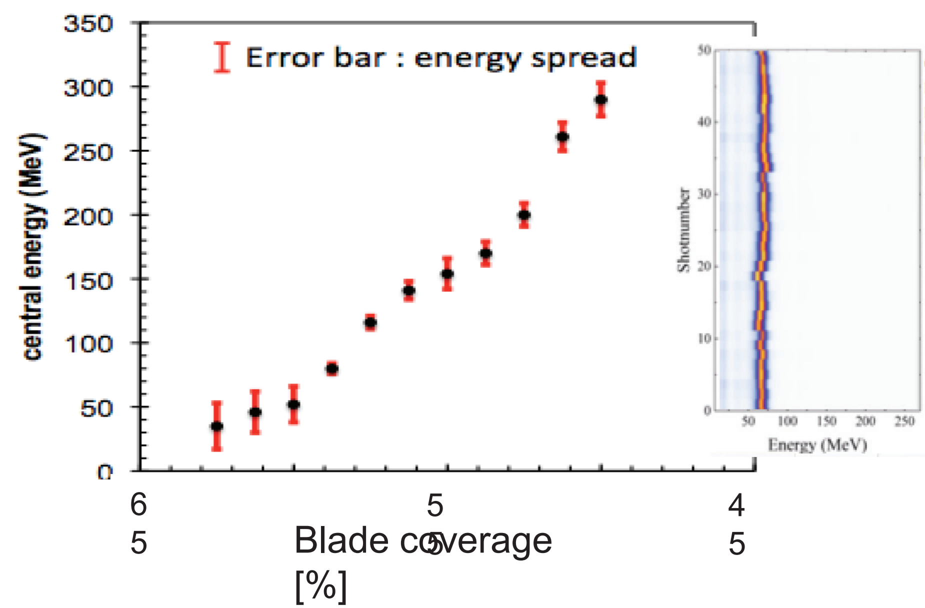
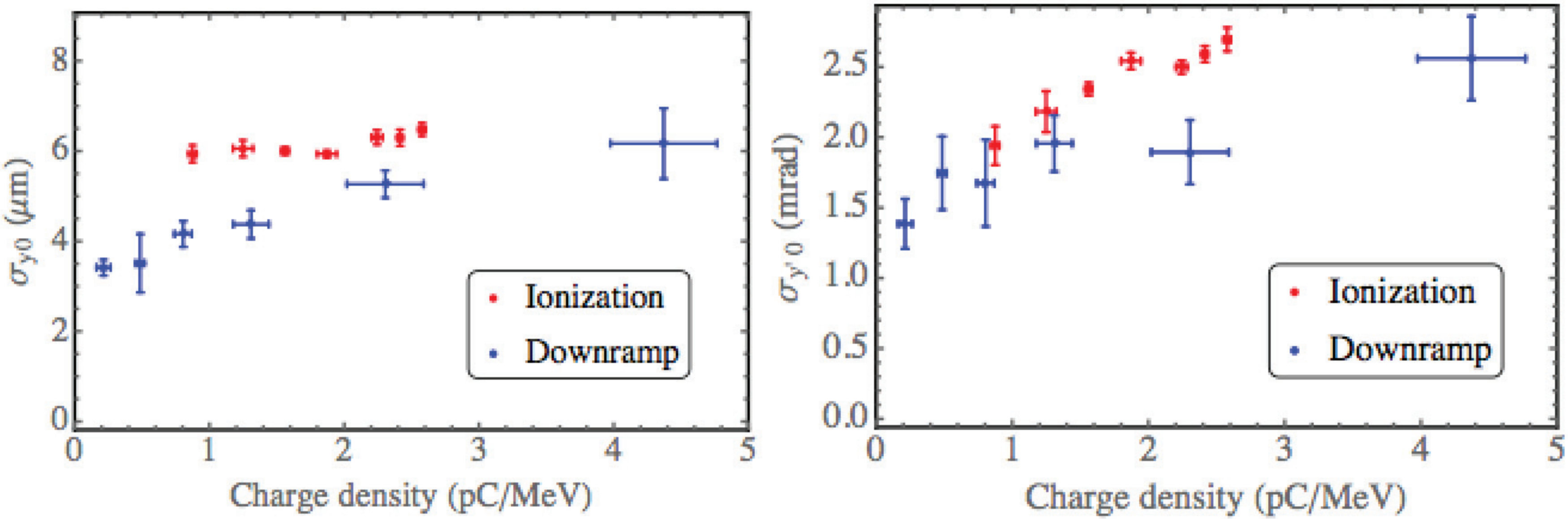

pC/MeV
0.6
0.3
0
125
100
75
50
25
0
Energy (MeV)
0.2 0.5 0.8
Blade coverage


Error bar : energy spread
central energy (MeV)
0 50 100 150 200 250 300 350
6
5
5
5
4
5
Blade coverage
[%]
Shotnumber
Energy (MeV)



$\sigma_{y0}$ (μm)
0
2
4
6
8
0
1
2
3
4
5
Charge density (pC/MeV)
Ionization
Downramp
$\sigma_{y'0}$ (mrad)
0.0
0.5
1.0
1.5
2.0
2.5
Charge density (pC/MeV)
Ionization
Downramp

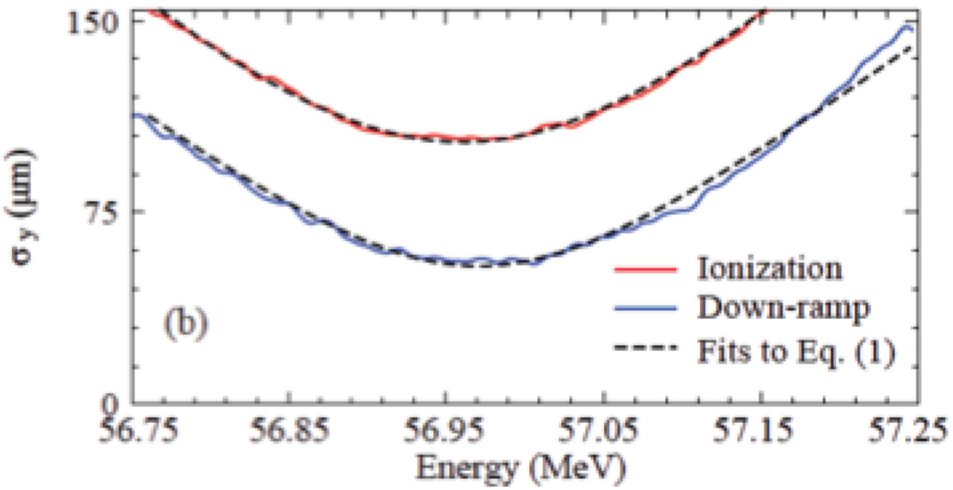
# Higher order transport terms can influence the emittance measurements (only at large divergence)

$$\sigma_y(E) = \sigma_{y0}\sqrt{\left([R_{34}(E^*)]^2 + [T_{346}(E^*)]^2 \frac{\beta_x \epsilon_x}{\gamma^2 \eta_x^2}\right)\left(\frac{\epsilon_y}{\gamma \sigma_{y0}}\right)^2 + [R_{34}(E^*)]^2 \sigma_{y0}^2}$$

$$\sigma_y(E) = \sqrt{[R_{34}(E^*)]^2\left(\frac{\epsilon_y}{\gamma\sigma_{y0}}\right)^2 + [R_{33}(E^*)]^2\sigma_{y0}^2}, \quad (1)$$

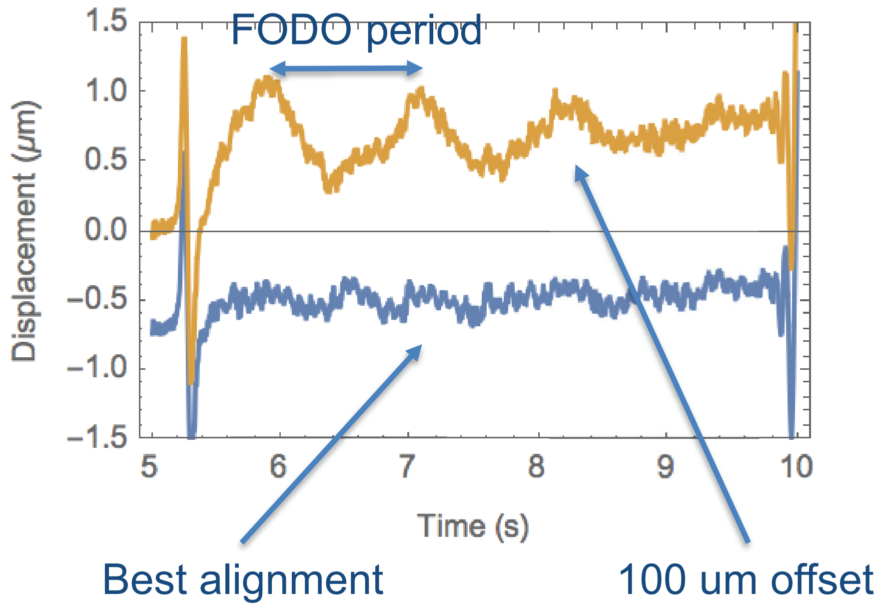
$$R_{33}(E) = 0.91(E-57) - 14$$
$$R_{34}(E) = 0.21(E-57)$$

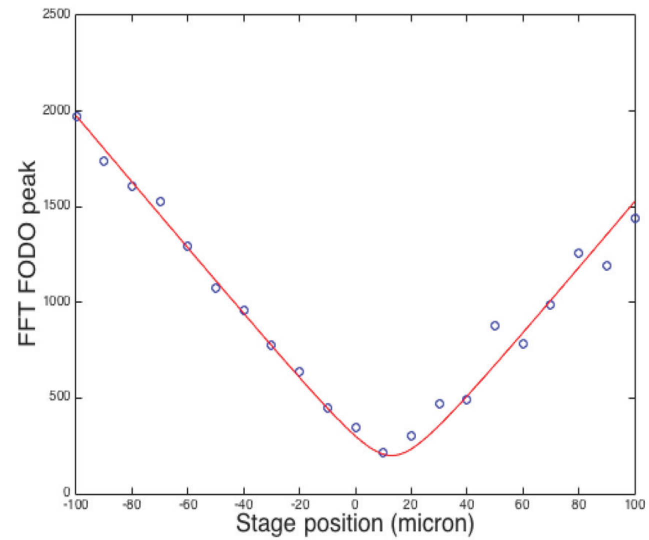
- Includes coupling divergence and energy resolution
- Need to rely on good design of transport lattice and good characterization of all transport elements
- Still, need to consider influence of uncertainty in the lattice, i.e. positioning error PMQ




Including 2nd order optics, the function describing $\sigma_y(E)$ becomes more complicated

# Critical goal: align and fiducialize undulator. Confident that we can realize <50 micron alignment accuracy




- Magnetic axis located with ~5 micron precision
- With laser tracker, all fiducial points located with 10 micron precision
  - ➢ Can define ideal e-beam axis well within 50 microns

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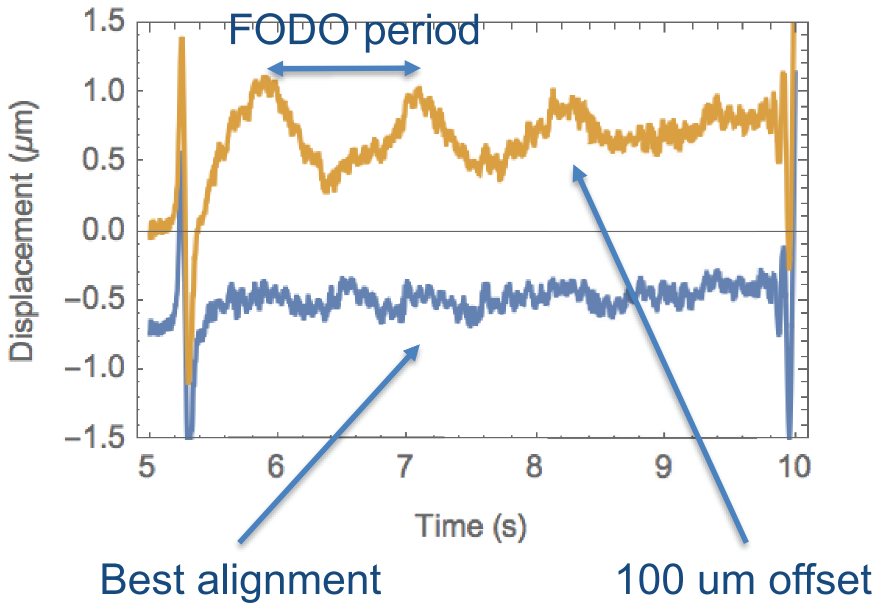


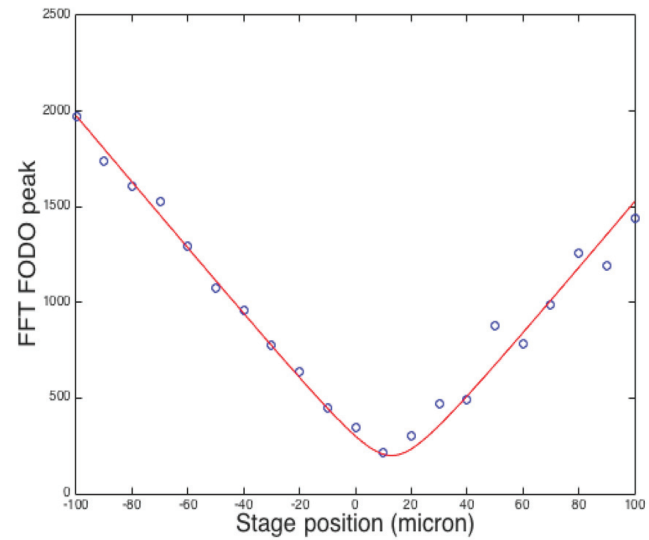


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