Realizing an FEL from a Laser Plasma Accelerator: Progress and Plans at LBNL

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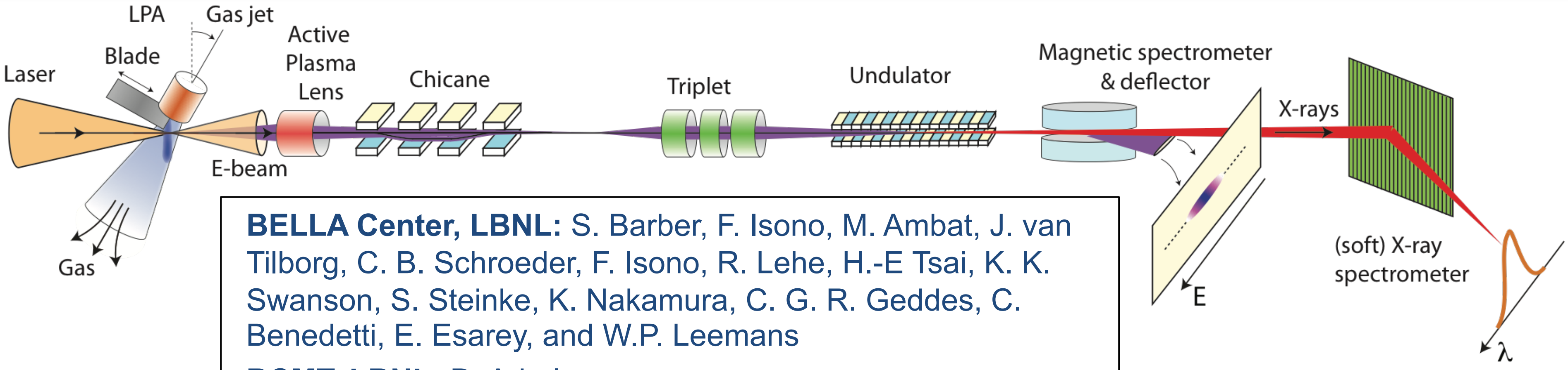
Office of Science
GORDON AND BETTY MOORE FOUNDATION
NSF

Goal: take advantage of high-brightness Laser Plasma Accelerators to drive compact FEL

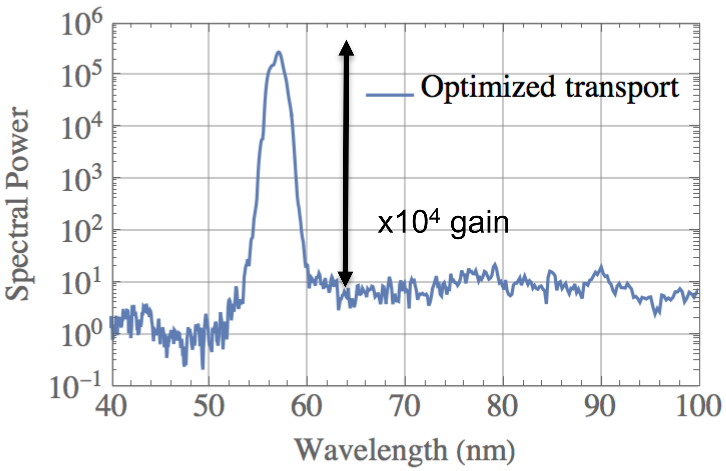


BELLA Center, LBNL: S. Barber, F. Isono, M. Ambat, J. van Tilborg, C. B. Schroeder, F. Isono, R. Lehe, H.-E Tsai, K. K. Swanson, S. Steinke, K. Nakamura, C. G. R. Geddes, C. Benedetti, E. Esarey, and W.P. Leemans

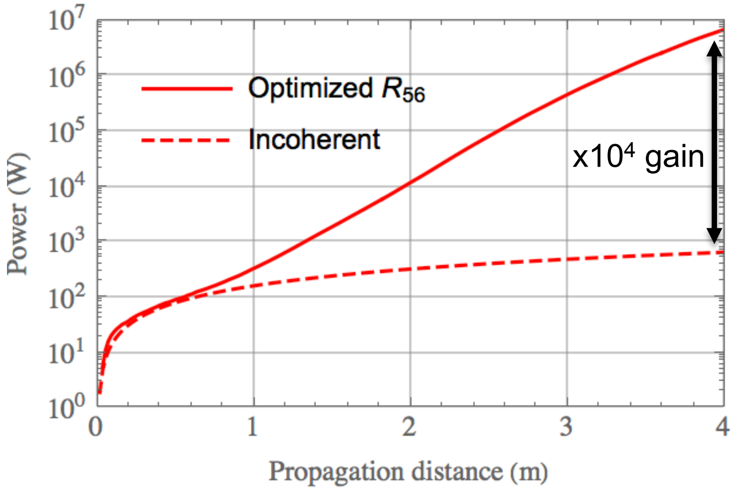
BCMT, LBNL: D. Arbelaez

Department of Physics, UCLA: G. Andonian, N. Majernik, R. Patil, and J. Rosenzweig

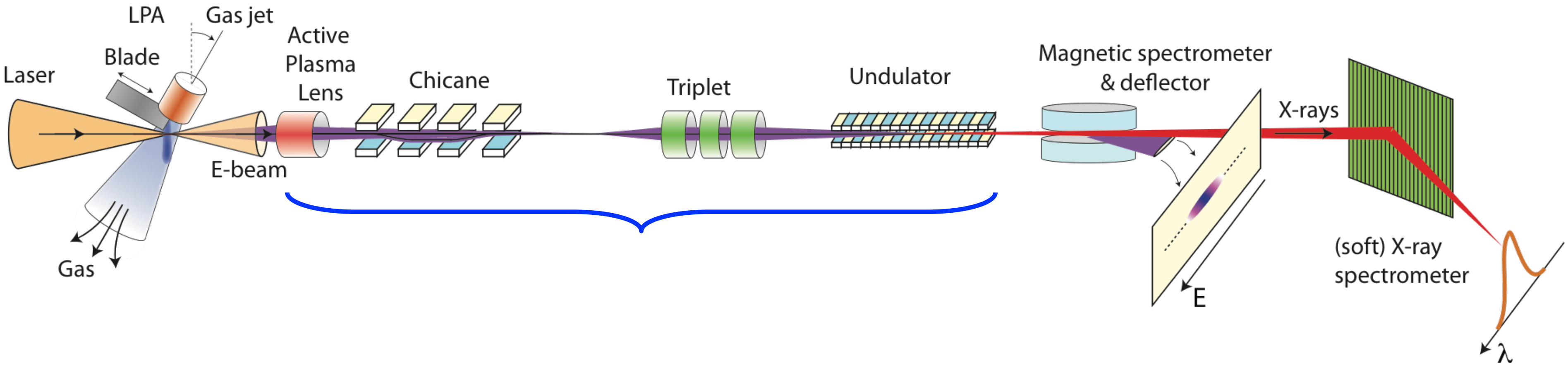
Goal:
275 MeV, 25 pC, 1% dE/E



Intermediate milestone:
100 MeV, 25 pC, 2.5% dE/E



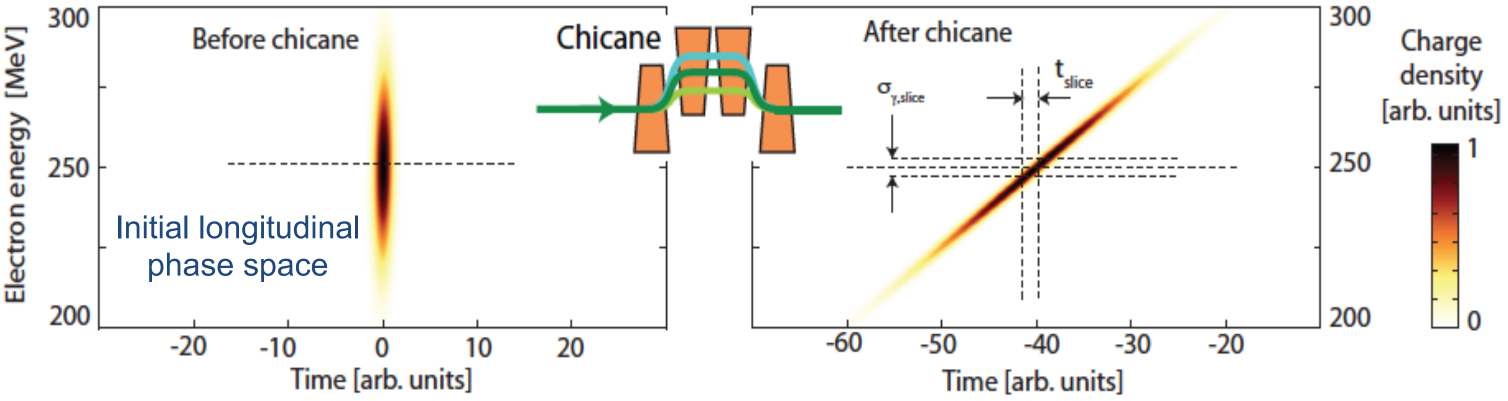
Beamline is designed to optimize FEL performance and scale e-beam energy (100-300 MeV)



Key components of the beamline:

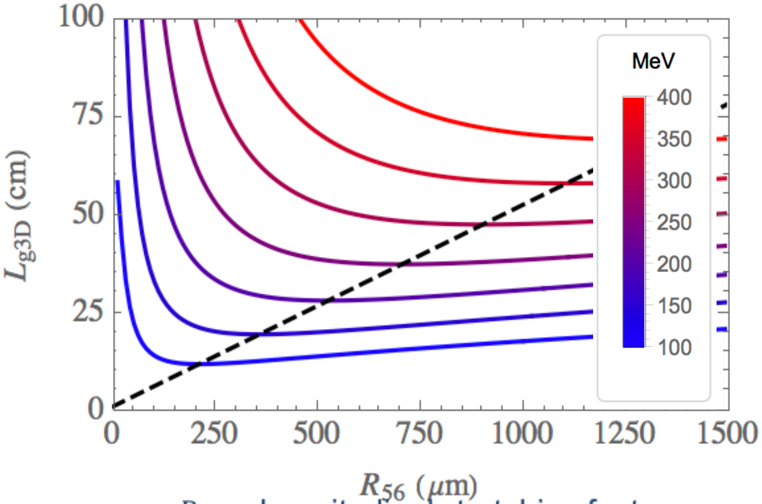
- First focusing element: active plasma lens (APL) or permanent magnet quadrupole (PMQ) triplet
- Chicane to stretch e-beam and reduce slice energy spread
- EM Triplet to deliver matched e-beam at undulator entrance
- 4m VISA undulator

LPA source brightness is good for FEL, slice energy spread is not: Use chicane to stretch beam, reduce slice energy spread



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

- FEL cares primarily about slice parameters
- Stretching can be optimized to minimize FEL gain length: find balance between reduction in beam current and slice energy spread
- Optimal R_{56} depends on initial beam parameters



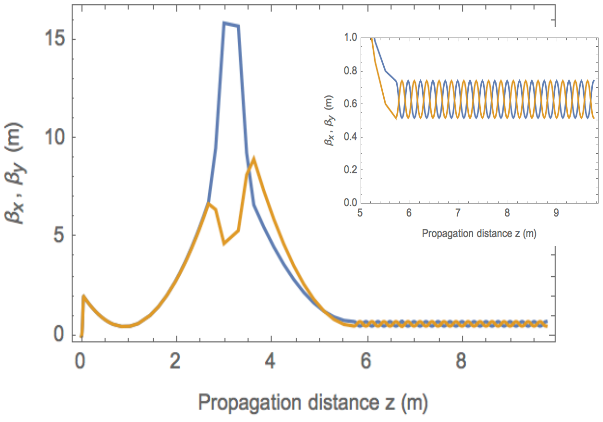
R_{56} =Longitudinal stretching factor

Details of transport are important to understand performance goals

Simulations are performed using a suite of tools:

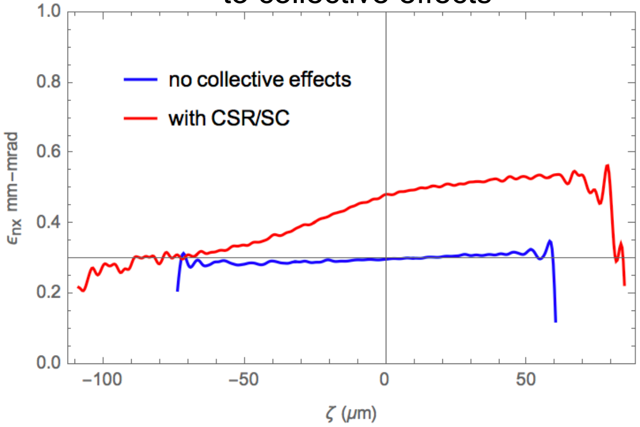
- Elegant for lattice optimization and matching routines
- Full particle tracking with collective effects, CSR modeled in elegant, space charge with Astra
- Final particle distribution ported to Genesis, 10 time dependent simulations with different shot noise seeds are run

Matching to VISA FODO lattice



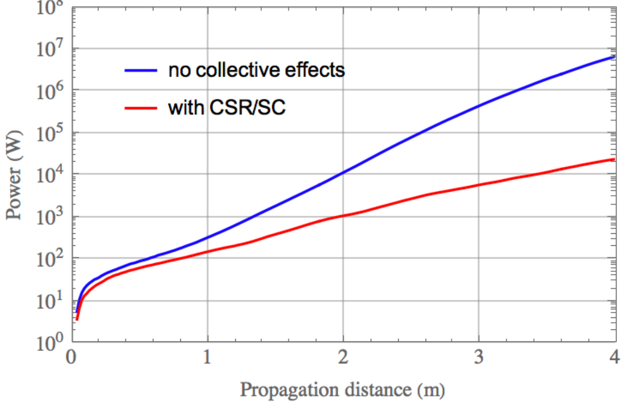
M. Borland LS-287. , 2000.

Slice emittance growth due to collective effects



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

Peak power vs. distance in VISA undulator

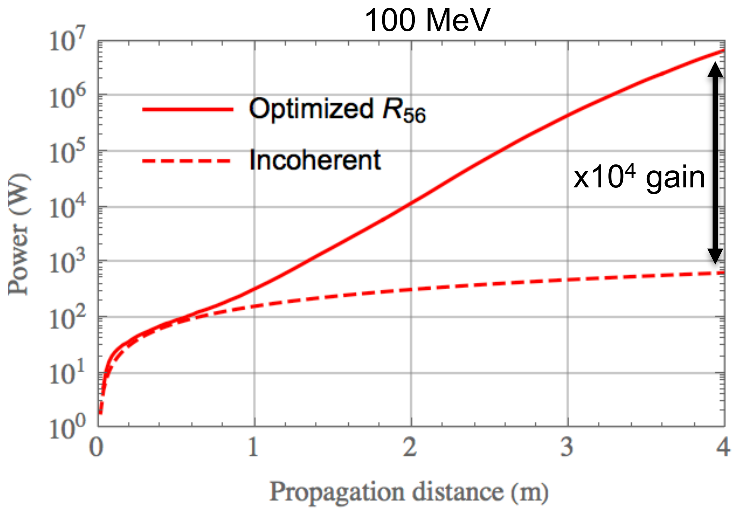


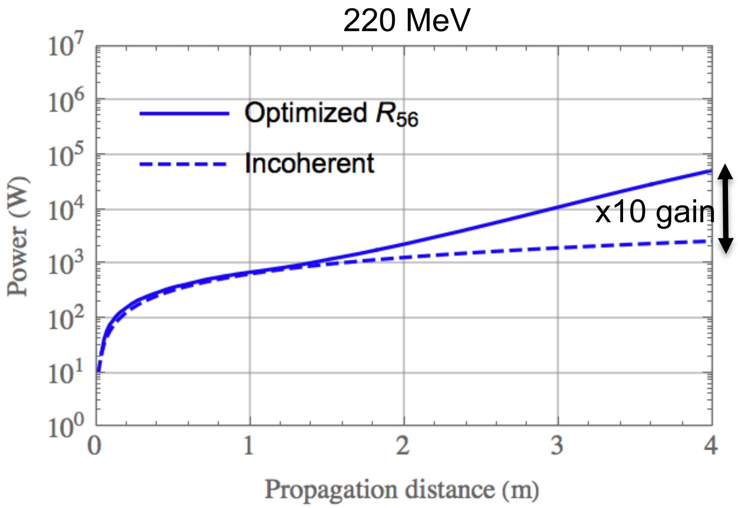
S. Reiche. NIMA, 429, 1999.

BELLA Center FEL project: Demonstrate FEL gain at 100 MeV, ramp up to ~300 MeV

Interest in FELs stems from ability to make compact, short pulse, x-ray wavelength laser

- Wavelength scales like $1/\gamma^2$
- but gain length as $L_g \sim \gamma$ → easier to demonstrate gain at low energy
- Nominal goal of 25 pC, 2.5% dE/E, ε_n=0.3 µm, source bunch length 1 µm


100 MeV

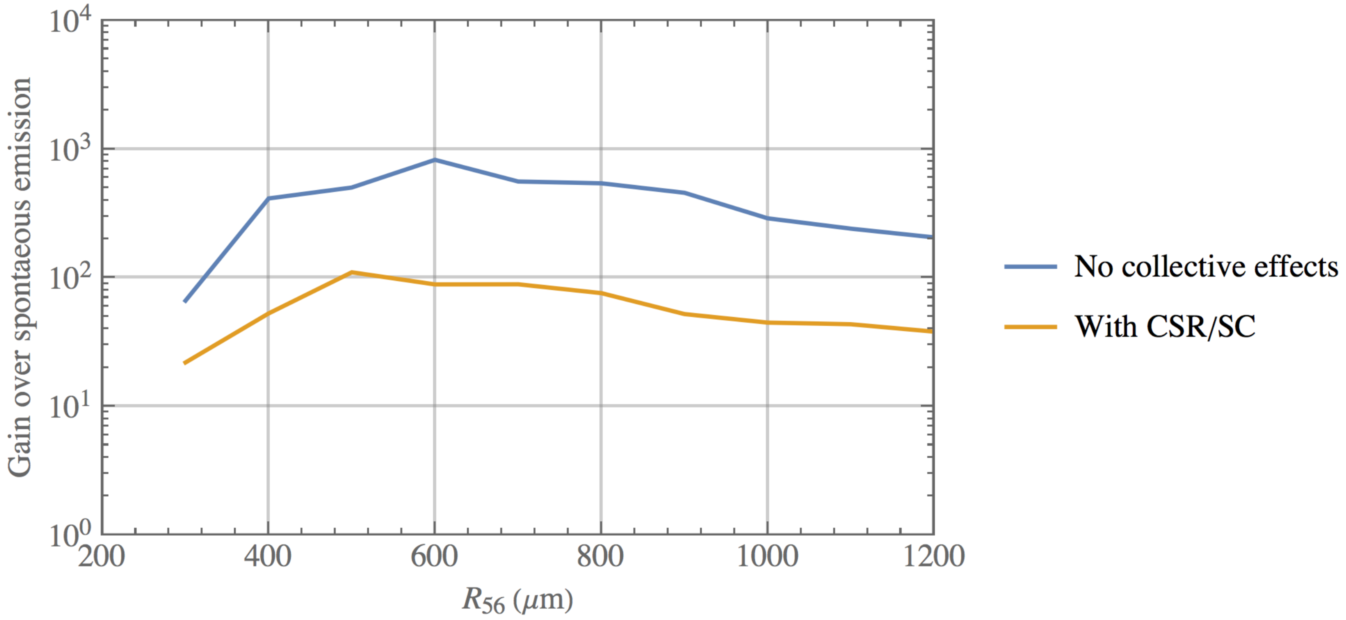

220 MeV

R_{56} =Longitudinal stretching factor

Increased brightness allows pushing the FEL to higher energy/ shorter wavelengths

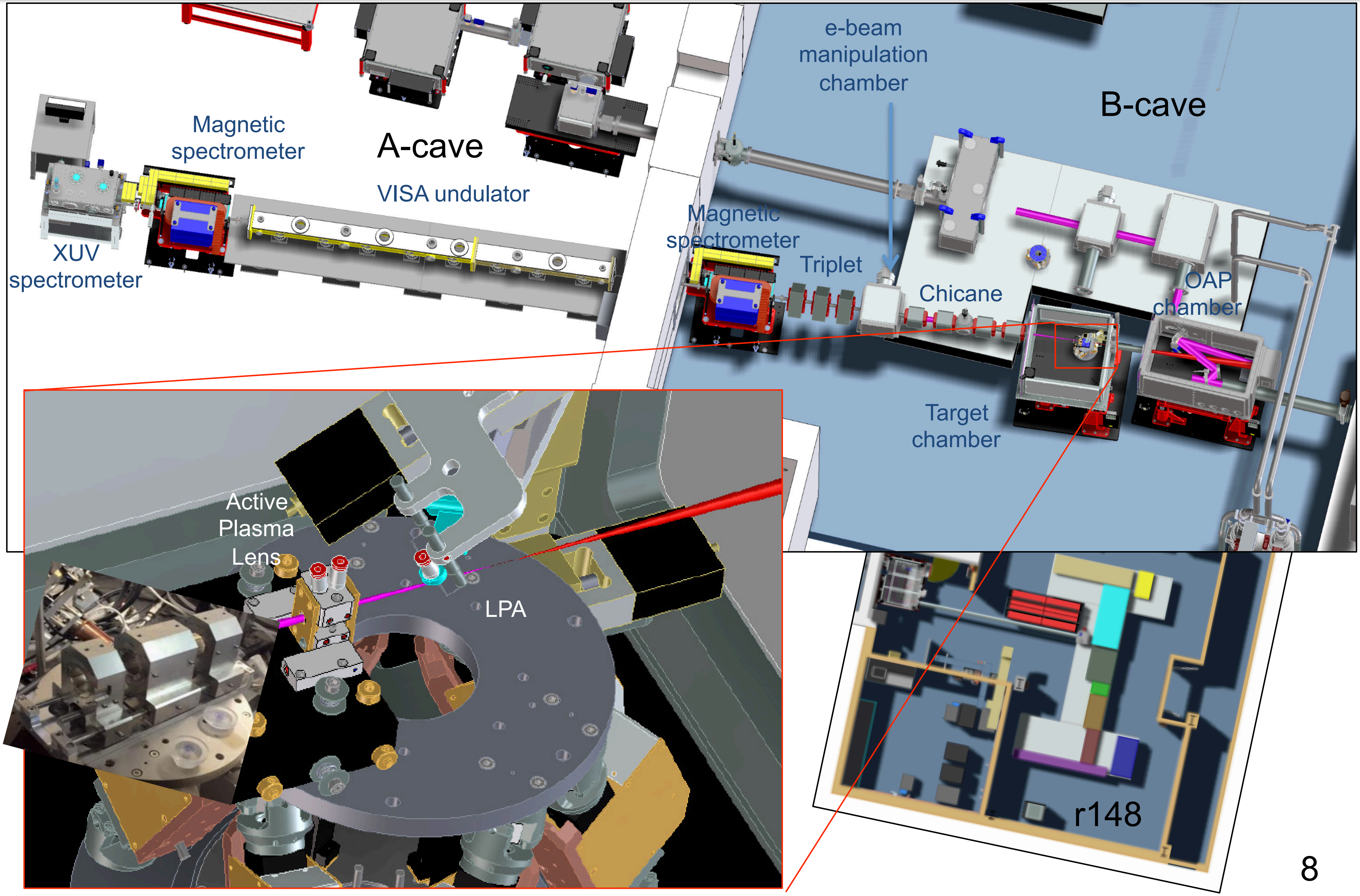
Nominal parameters: 25 pC, $\sigma_\gamma = 1.0\%$, $\varepsilon_n = 0.3\ \mu m$, $\sigma_z = 1.0\ \mu m$

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



With VISA 275 MeV→ λ_l=50 nm

Couple new laser room 148 to existing radiation caves in an optimized transport configuration

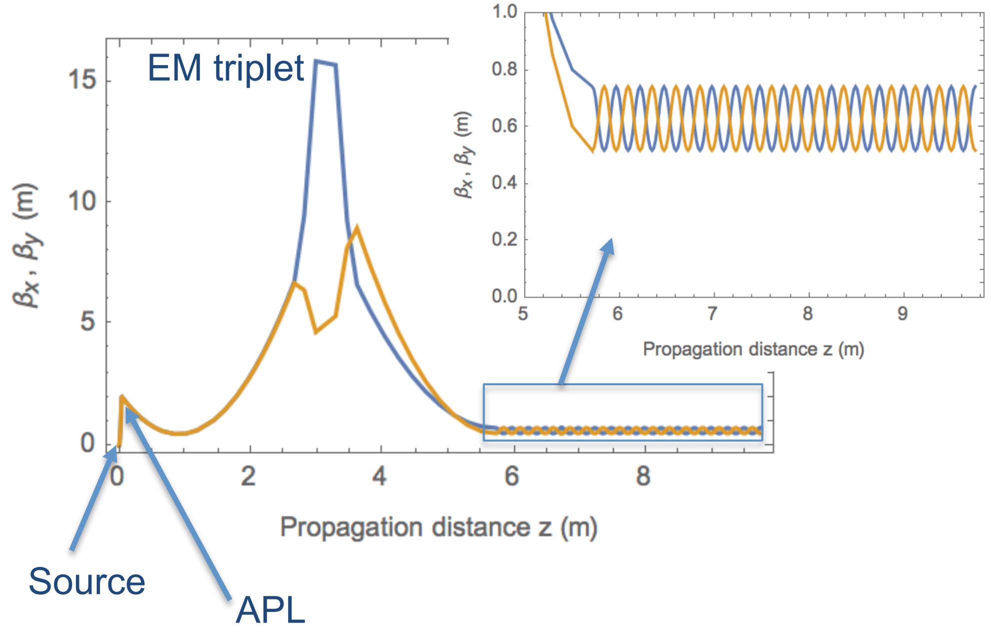


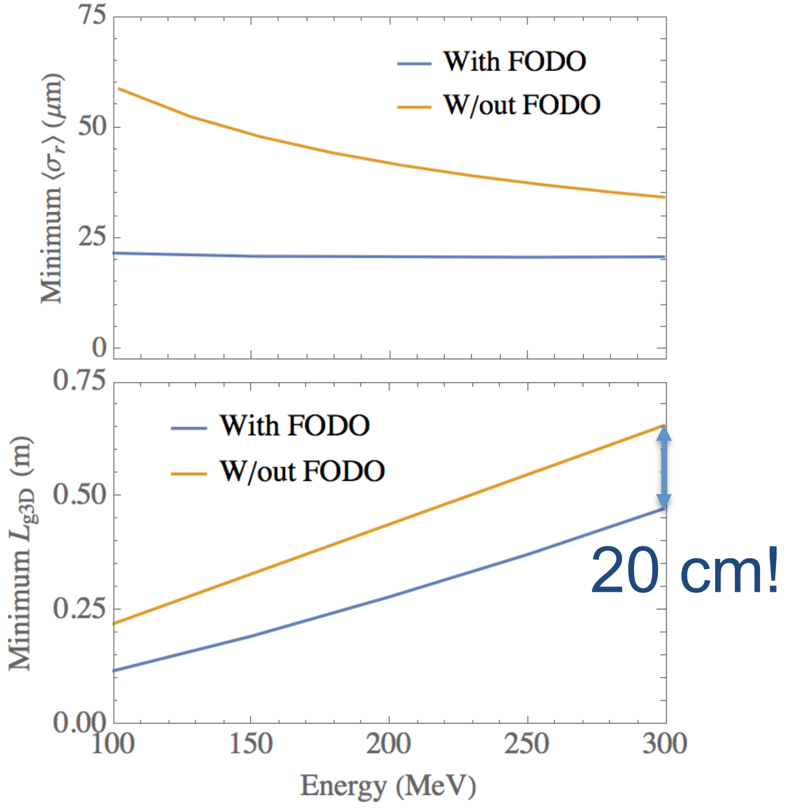
VISA undulator designed for demonstration of SASE saturation in short distance, perfect for LPA driven FEL

- Experiments at ATF were among the first to reach FEL saturation in only 4m[1,2]
- Unique feature: embedded quadrupole focusing (FODO lattice) with 33 T/m gradient
  - With FODO lattice: $\langle\beta\rangle \approx 0.0014\gamma$, no FODO: $\langle\beta\rangle_{min} = L_{und}/\sqrt{3}$

[1] Tremaine, A. et al. 2001.
[2] Murokh, A. et al. 2003

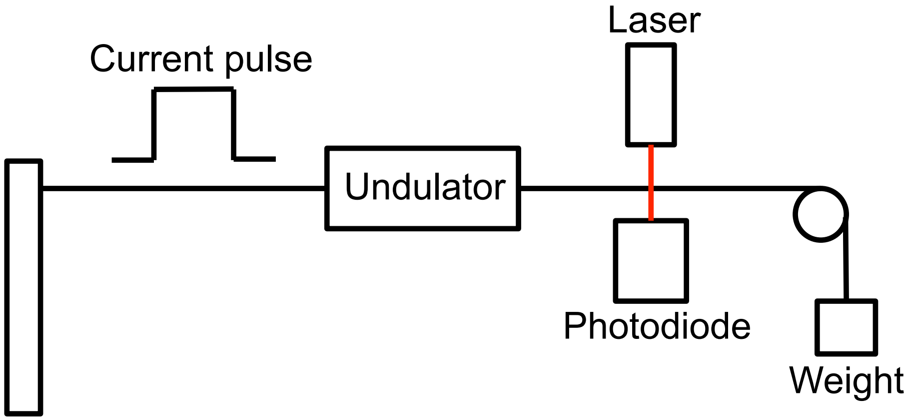
Parameter	Symbol	Value
Undulator period	λ_w	1.8 cm
Undulator length	L	4 m
Undulator Parameter	K $(\bar{K})$	1.26 (0.89)

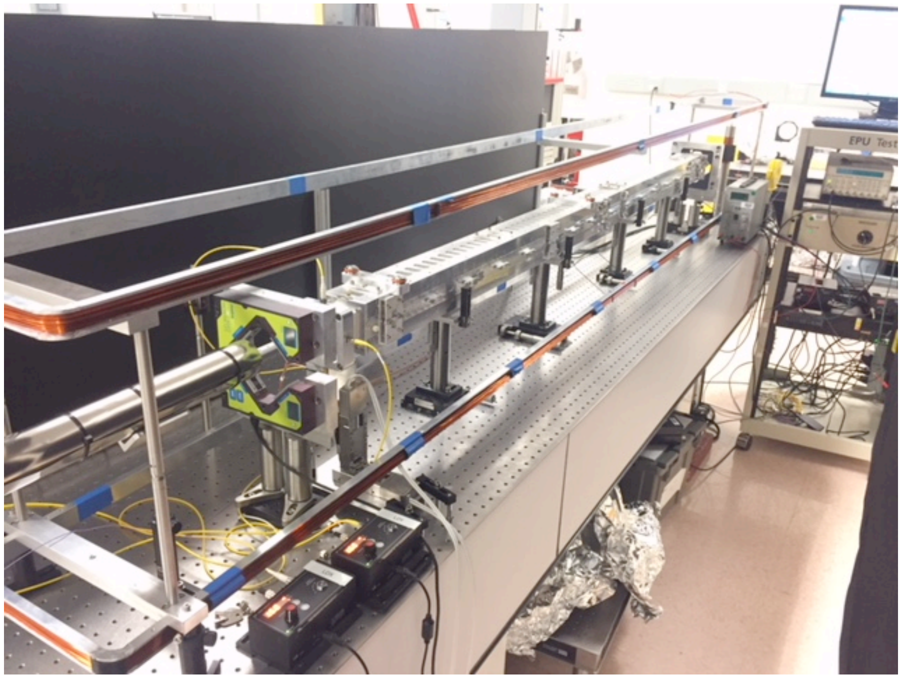


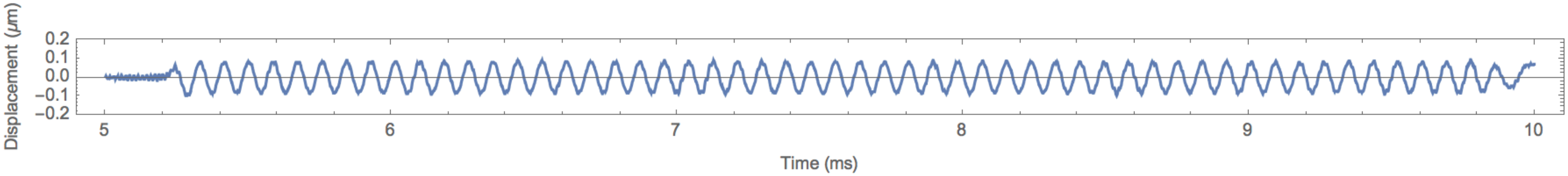


Assembled state-of-the-art magnet test bench for VISA undulator using pulsed wire method

Arbelaez *et al.* NIMA 2013



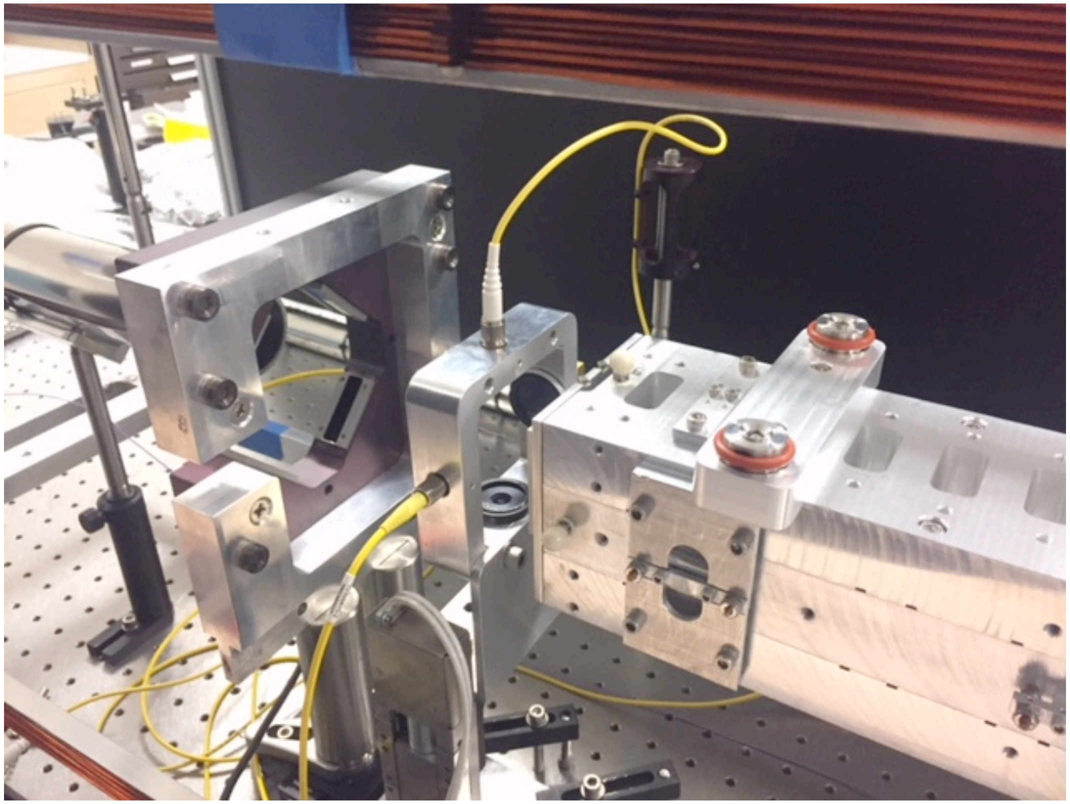


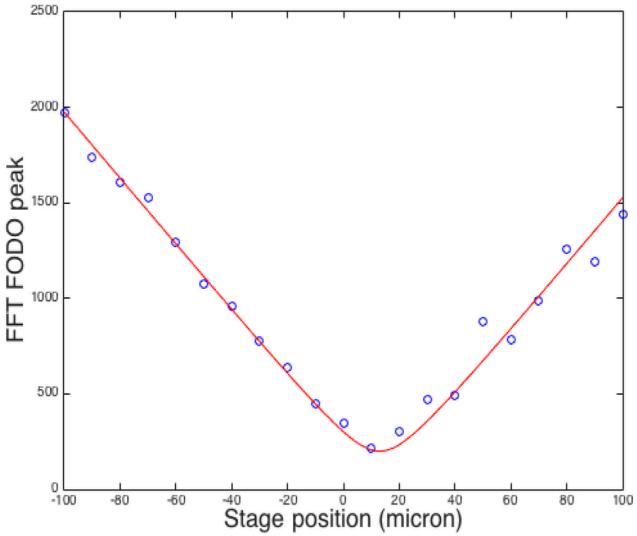


Measurement proportional to first field integral of 1m segment

Critical goal: Align and fiducialize undulator

- 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

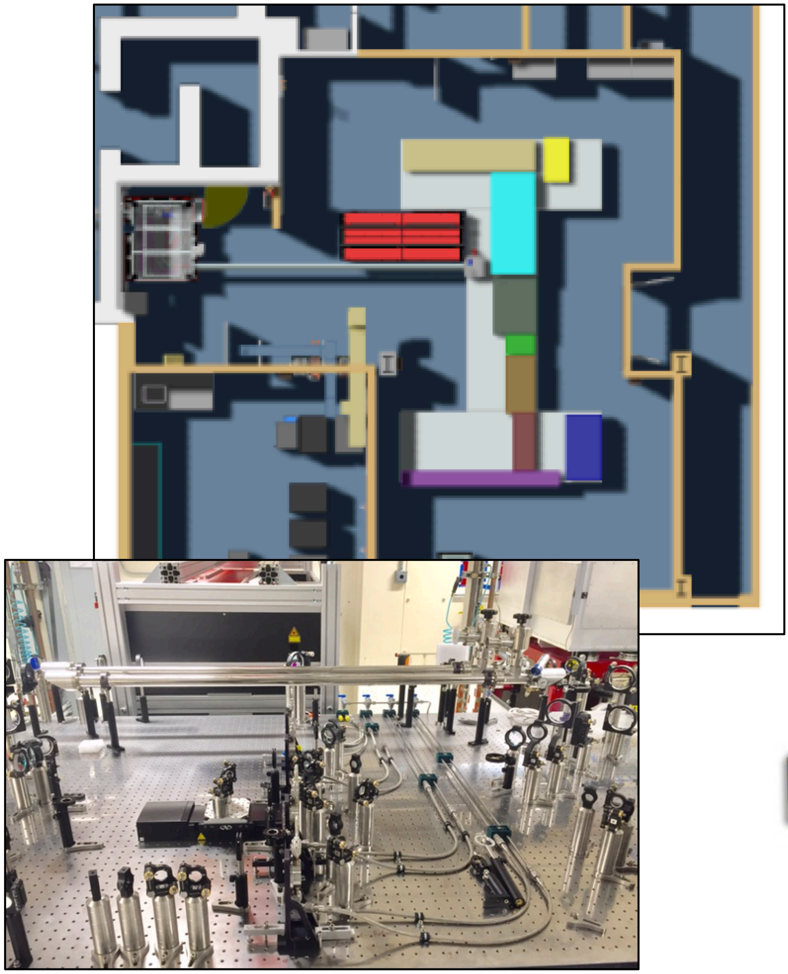


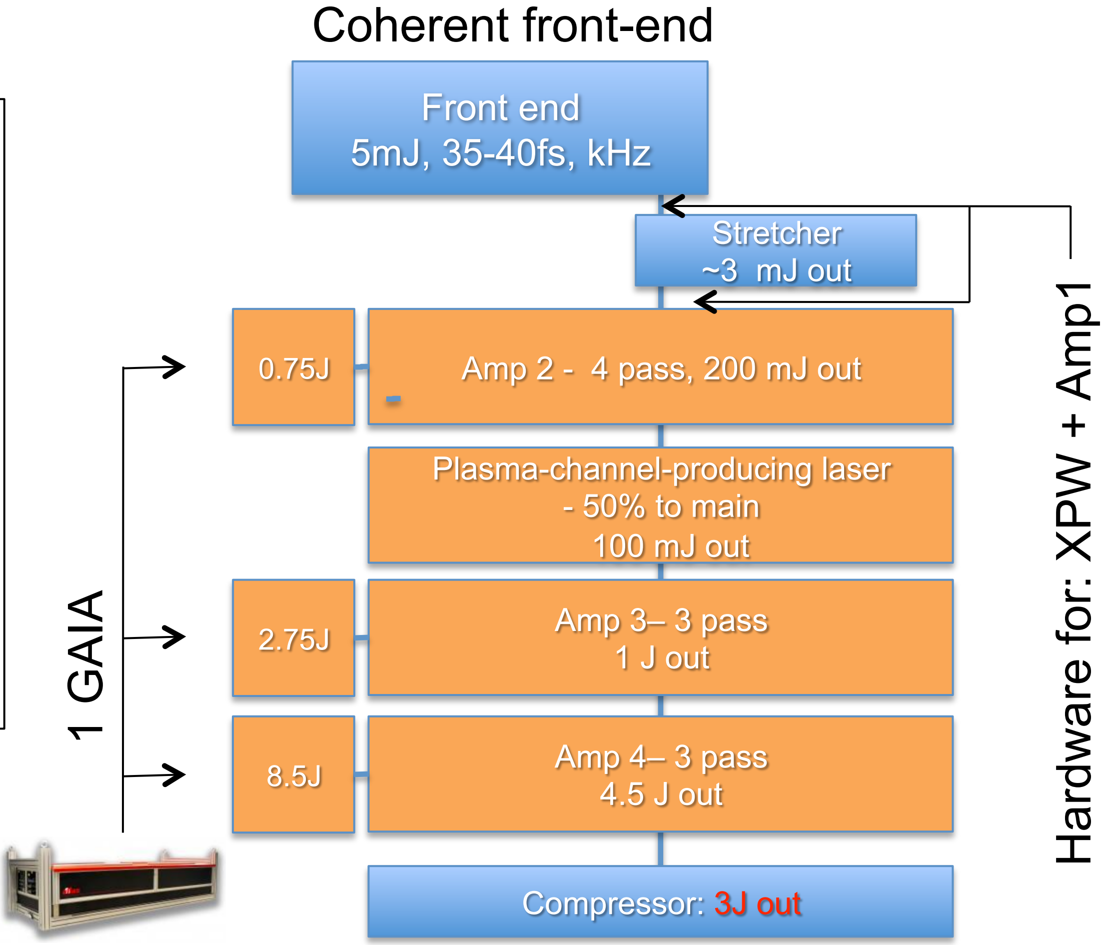


FEL-dedicated single-table laser system developed

100 TW laser system

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





Coherent front-end

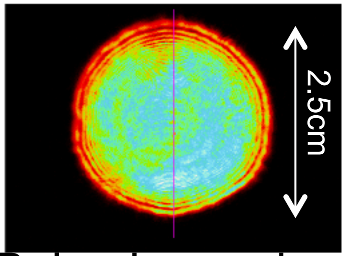
Front end
5mJ, 35-40fs, kHz

Stretcher
~3 mJ out

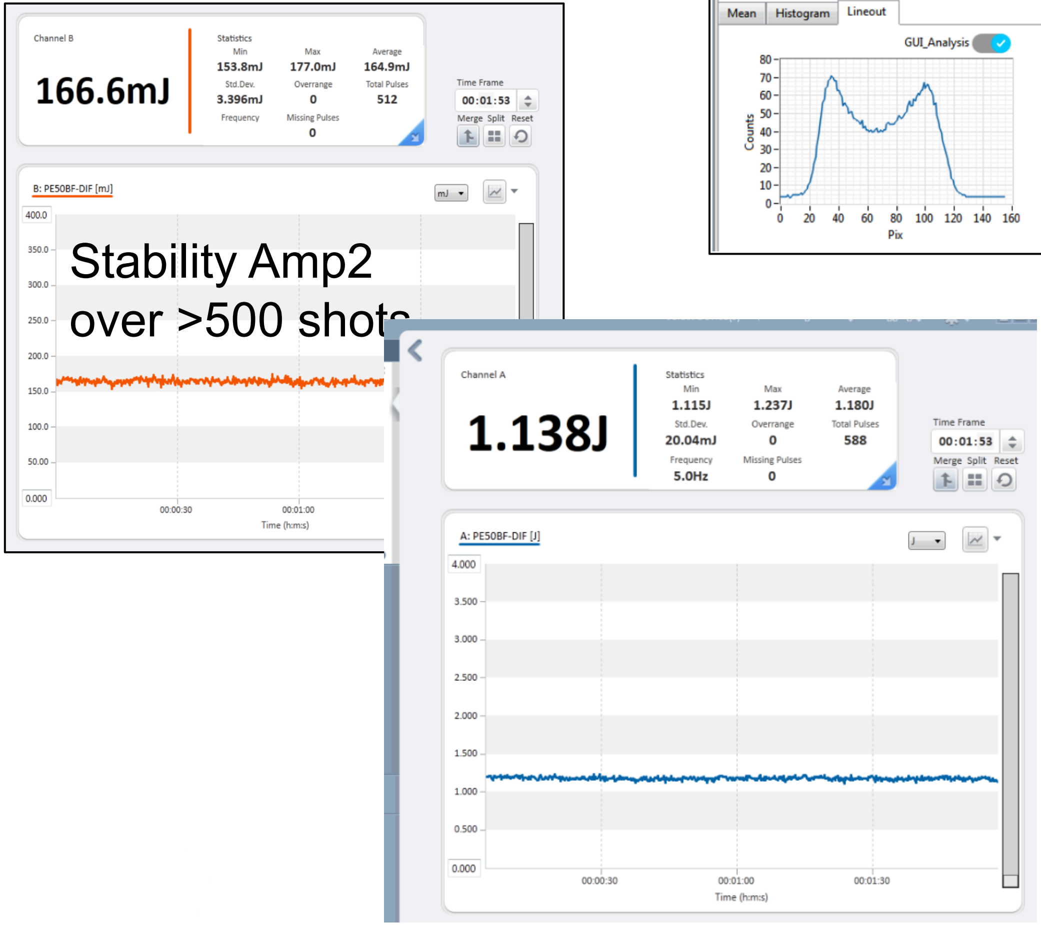
0.75J	Amp 2 - 4 pass, 200 mJ out
	Plasma-channel-producing laser - 50% to main 100 mJ out
2.75J	Amp 3– 3 pass 1 J out
8.5J	Amp 4– 3 pass 4.5 J out

Compressor: 3J out

GAIA issues Feb-Sept 2017 largely resolved
Amp2 & Amp3 operational (1.1J), on to Amp4 (4.5J)



Relay-imaged pump



Channel B

166.6mJ

Statistics

Min 153.8mJ

Max 177.0mJ

Average 164.9mJ

Std.Dev. 3.396mJ

Overrange 0

Total Pulses 512

Frequency

Missing Pulses 0

Time Frame 00:01:53

B: PE50BF-DIF [mJ]

Stability Amp2 over >500 shots

Channel A

1.138J

Statistics

Min 1.115J

Max 1.237J

Average 1.180J

Std.Dev. 20.04mJ

Overrange 0

Total Pulses 588

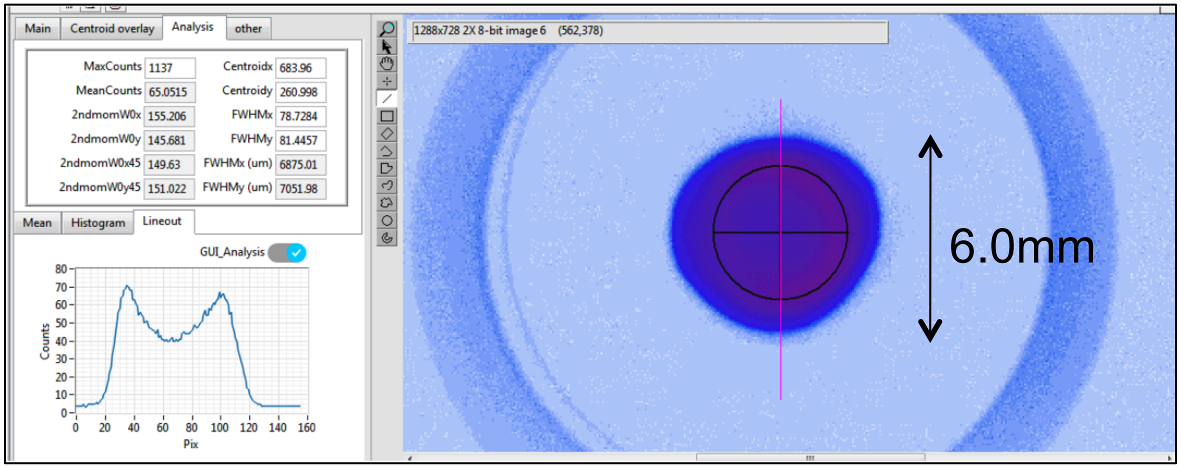
Frequency 5.0Hz

Missing Pulses 0

Time Frame 00:01:53

A: PE50BF-DIF [J]

Pump-induced spontaneous emission Ti:S



MaxCounts 1137

MeanCounts 65.0515

2ndmomW0x 155.206

2ndmomW0y 145.681

2ndmomW0x45 149.63

2ndmomW0y45 151.022

Centroidx 683.96

Centroidy 260.998

FWHMx 78.7284

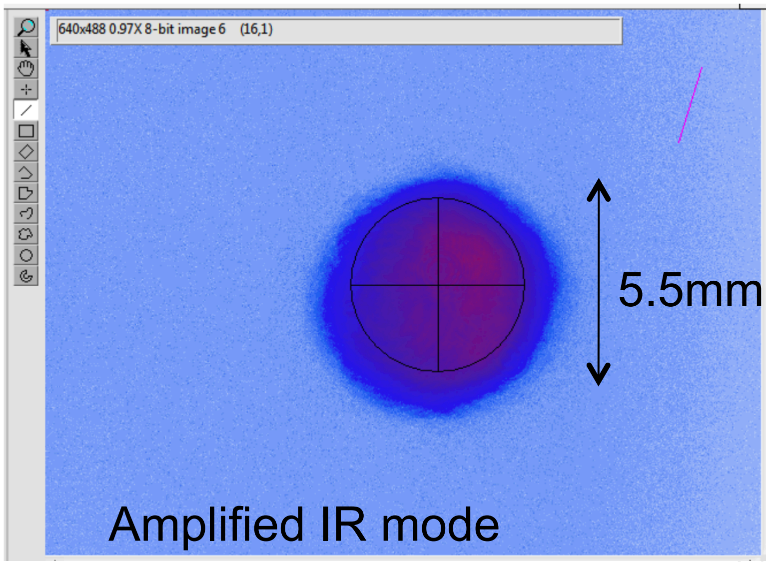
FWHMy 81.4457

FWHMx (um) 6875.01

FWHMy (um) 7051.98

GUI_Analysis ☑

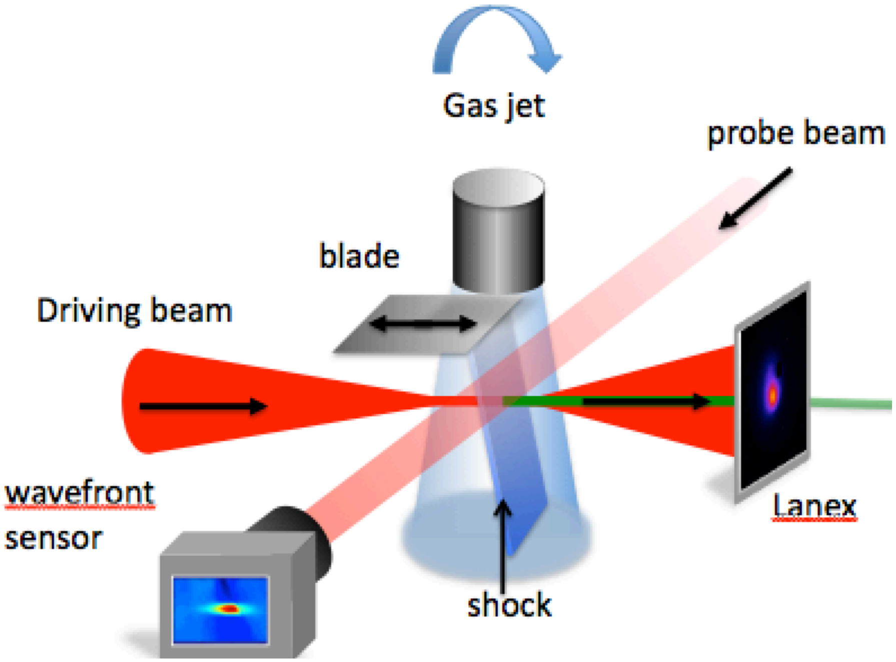
1288x728 2X 8-bit image 6 (562,378)

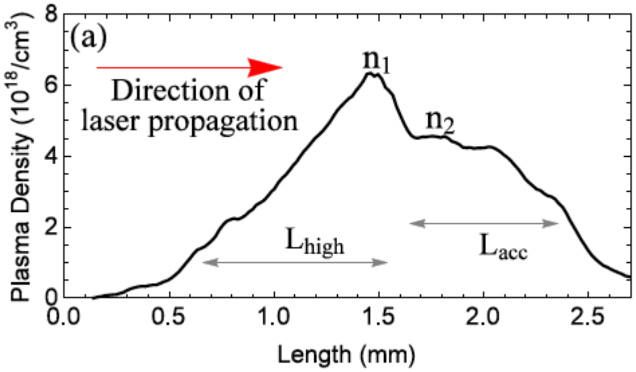


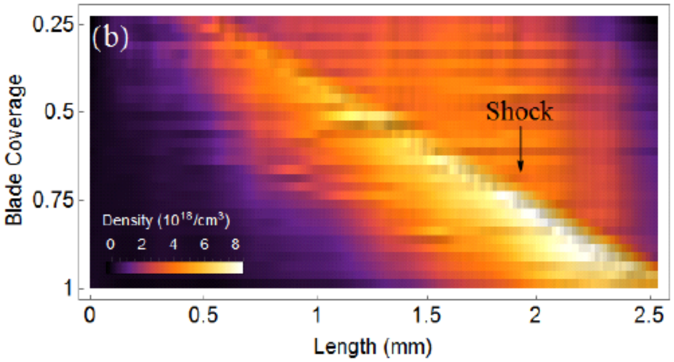
640x488 0.97X 8-bit image 6 (16,1)

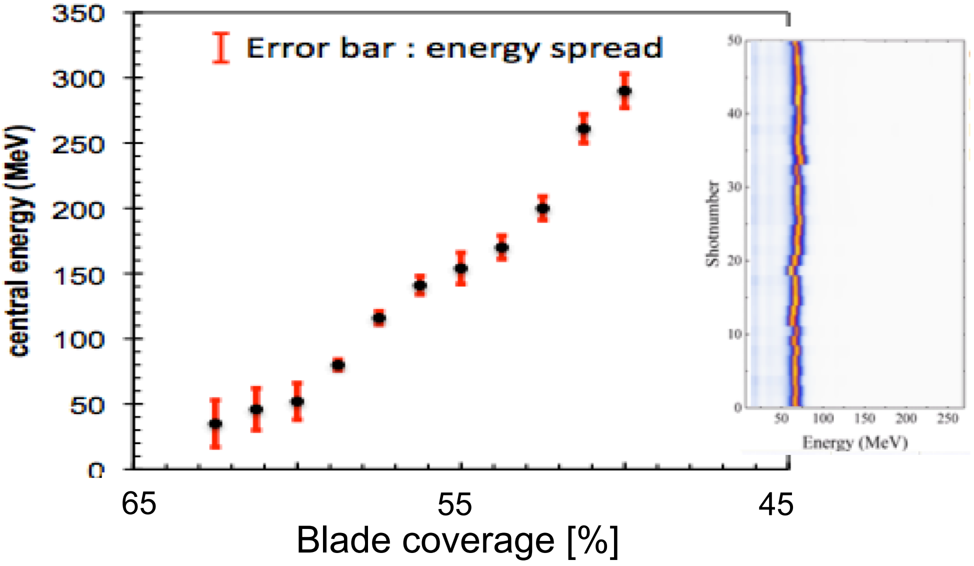
Amplified IR mode

Tiled jet-blade LPA developed
Proved to be stable & tunable, FEL-applicable





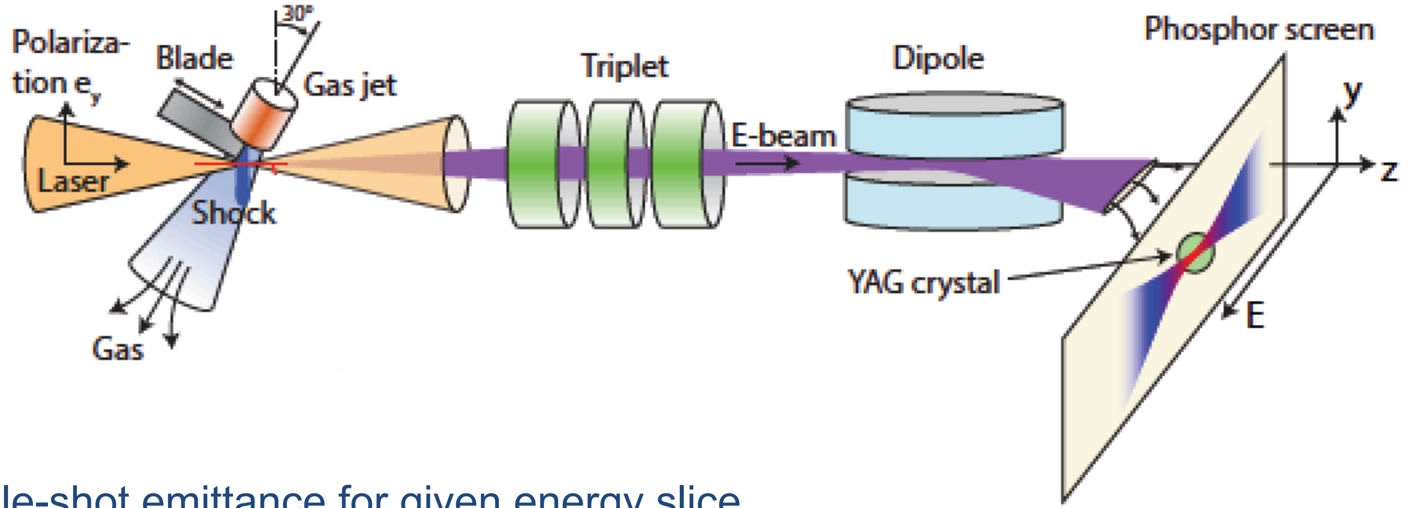




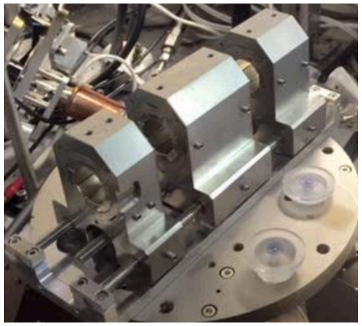
- Summer 2016 → LPA campaigns critical to FEL project performed
- Down-ramp provides controlled injection
- Tilted jet and extensive plasma characterization → optimum performance
- 10-50 pC, 2-6% dE/E, 50 to >200 MeV
- Alternative option to cap-based LPA

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

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

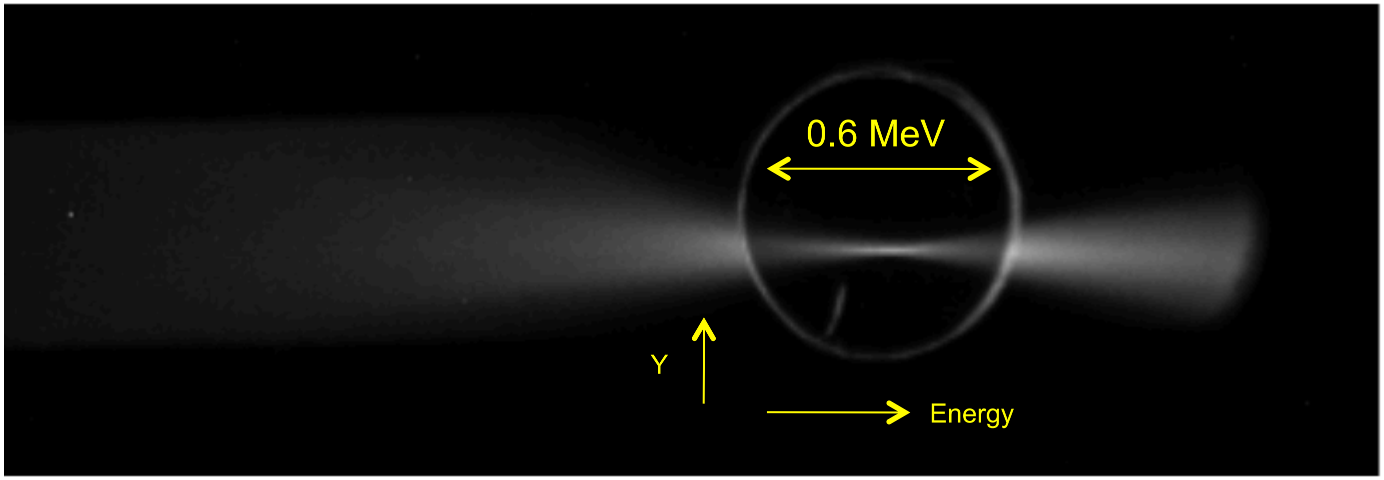


RadiaBeam triplet

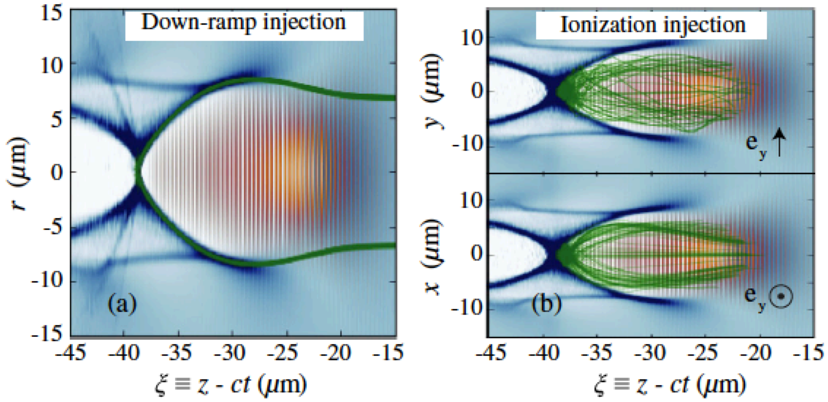


- Single-shot emittance for given energy slice
- Assumes emittance is constant within sub-% bandwidth
- LPA Technique first used by Weingartner *et al.* PRSTAB 2012
- We optimized spatial/energy resolution → LPA parameter scans

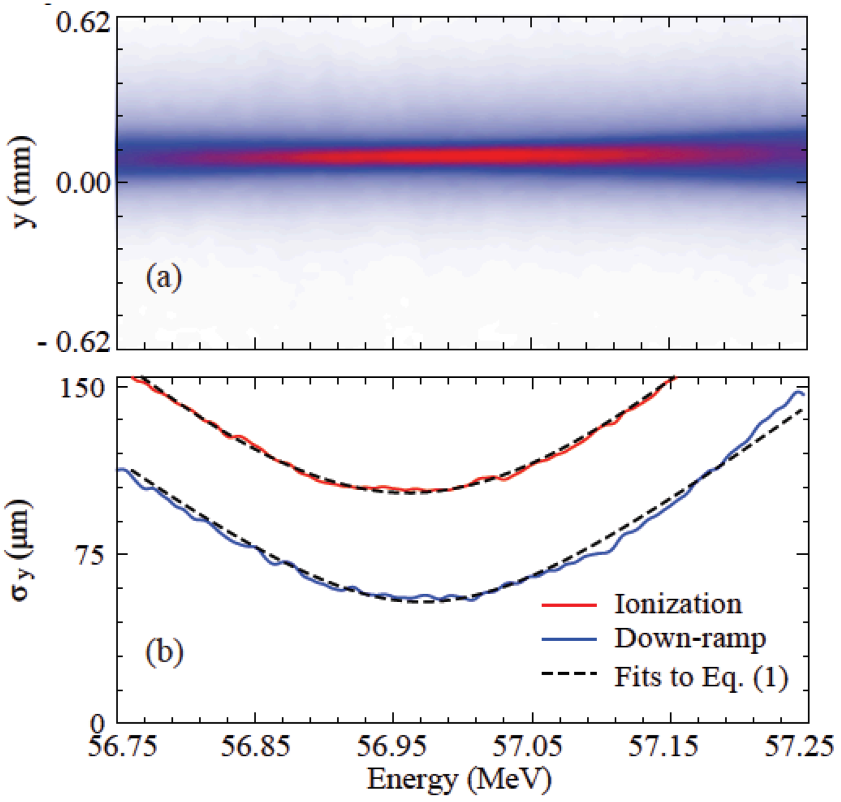
0.3mm thick YAG crystal

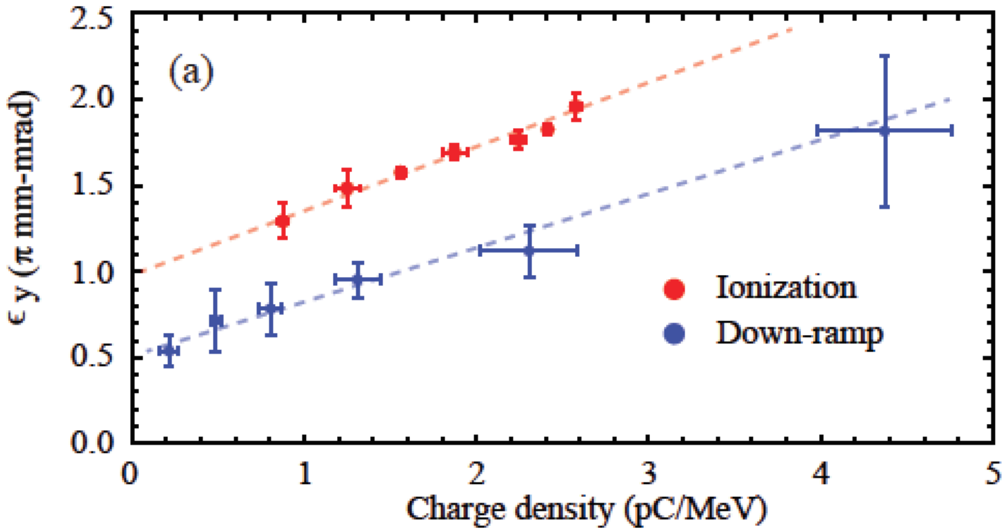


First direct observation of emittance dependence on injection mechanism



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





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

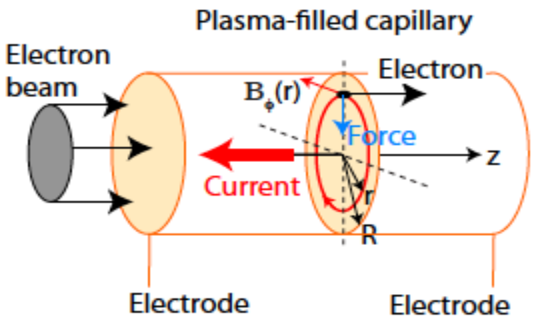
Need to quickly capture and focus e-beam with first focusing element: Active plasma lens

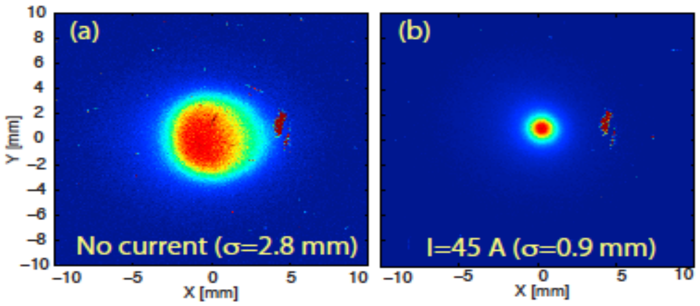
[1]van Tilborg *et al*. PRL **115**, 184802 (2015), [2]van Tilborg *et al*. PR-AB 20, 032803 (2017), [3]R. Pompli *et al*. APL 2017

Active plasma lens[1]:

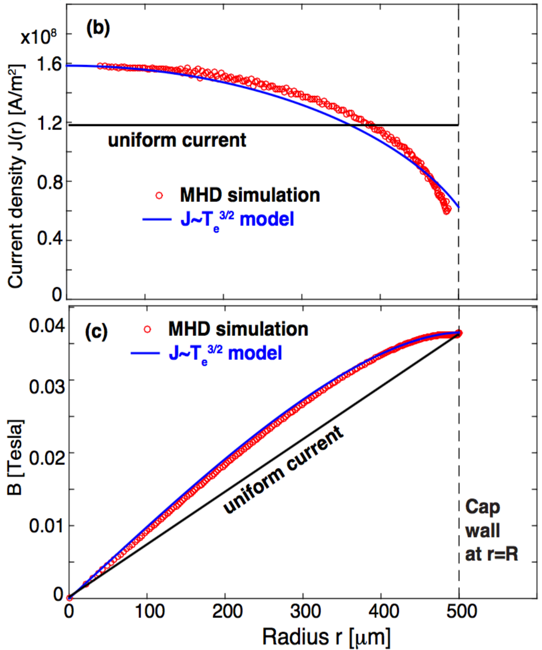
ultra high gradient (~kT/m), radially symmetric focusing, easily tunable.

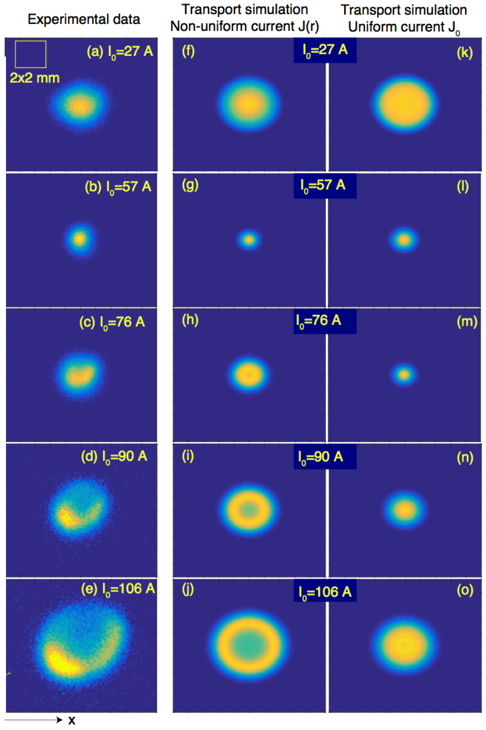
Work is ongoing to fully characterize these types of lenses: Need to understand e-beam driven wakefield limits, other beam-plasma instabilities, linearity/uniformity of field[2,3]





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



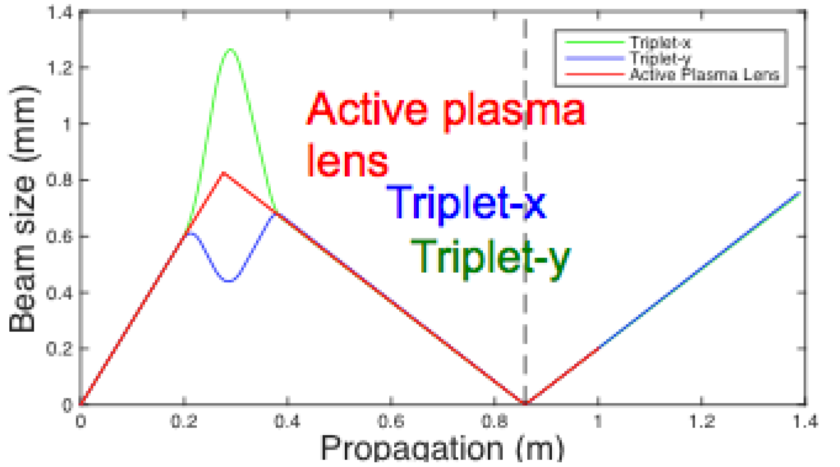


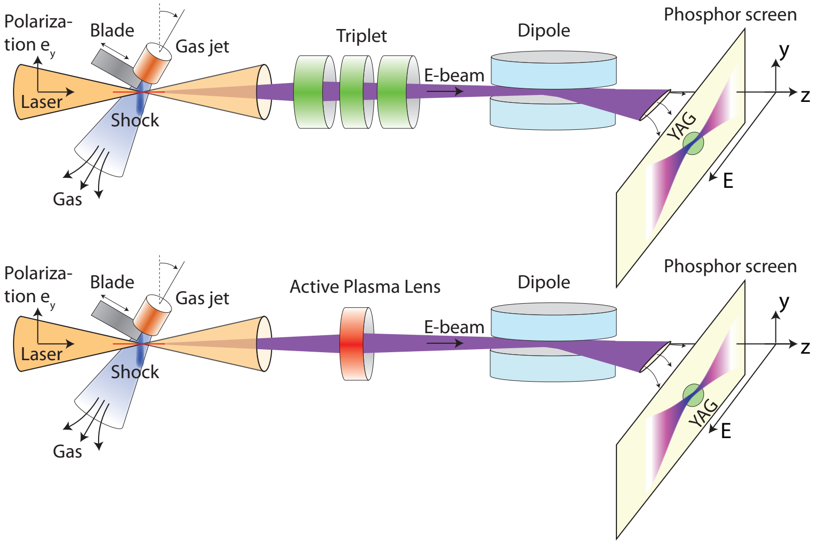
Non-uniform discharge current drives non-linear B-field

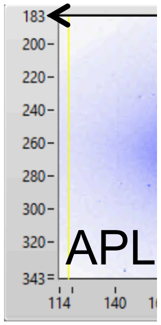
- Studied analytically & experimentally (agreement)
- Partial ionization (weak current) and cold walls (temp gradient): near-axis enhancement & non-linearity
- Linear B(r) for strong currents & beams with FWHM < Diameter/2

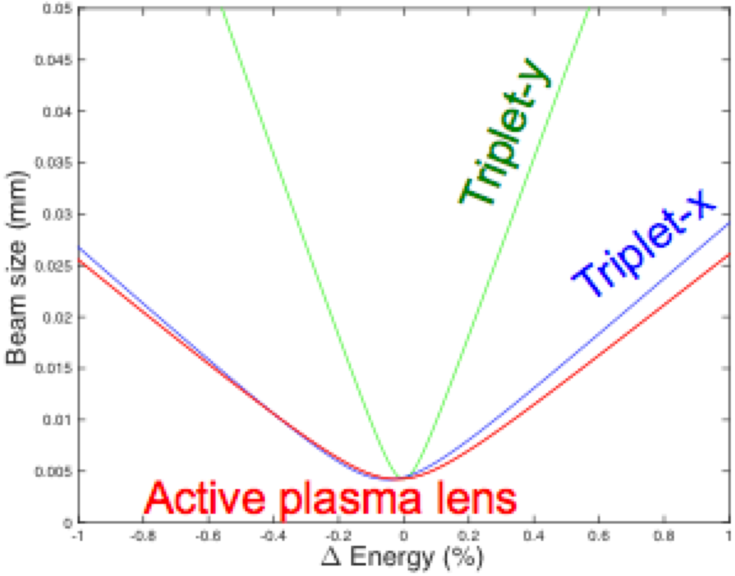
APL validated at BELLA PW.
Recent efforts: direct triplet/APL comparison

Comparison triplet & APL

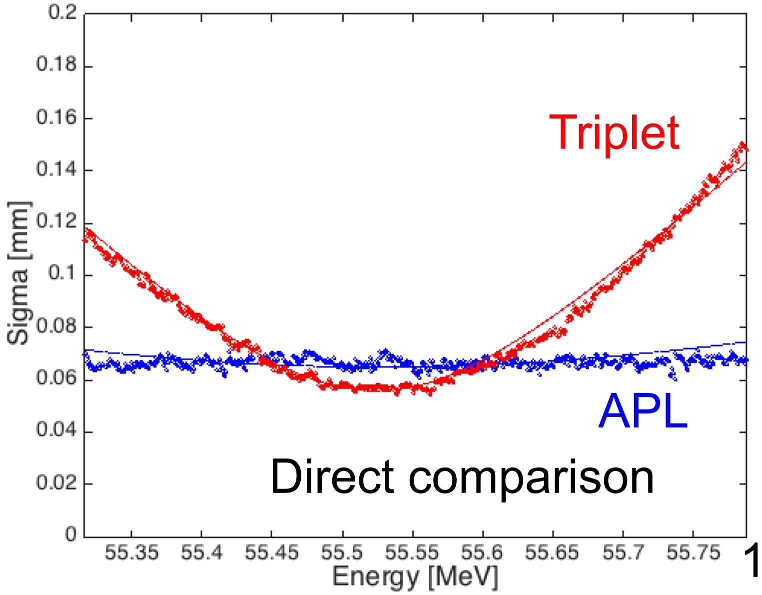






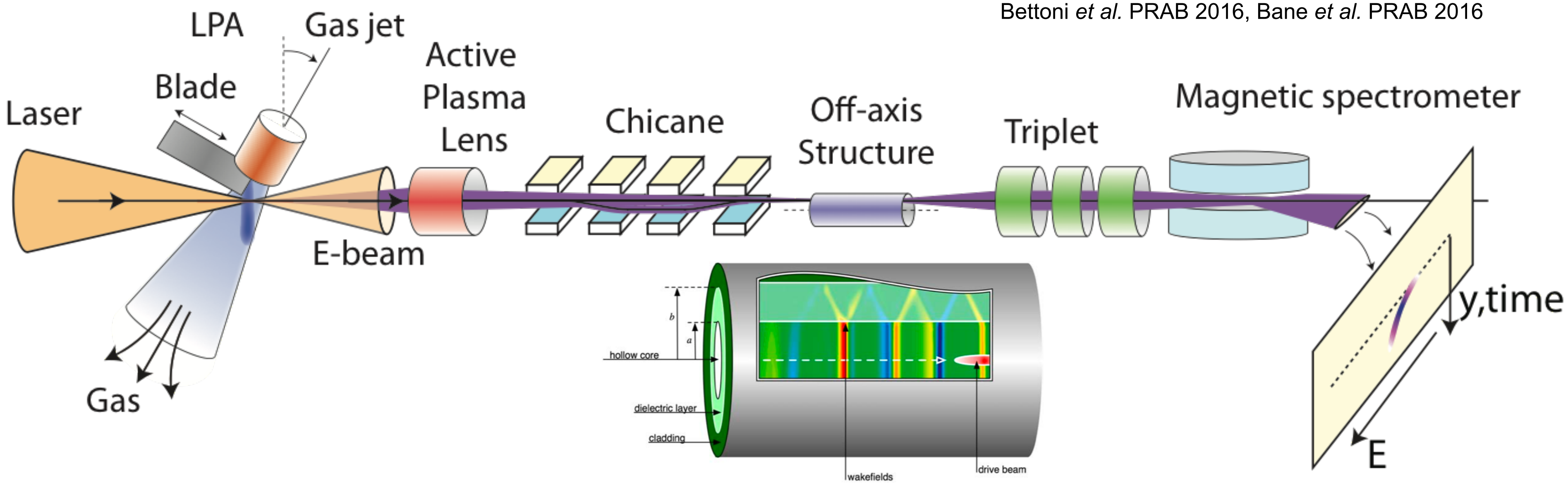


APL: weak chromaticity

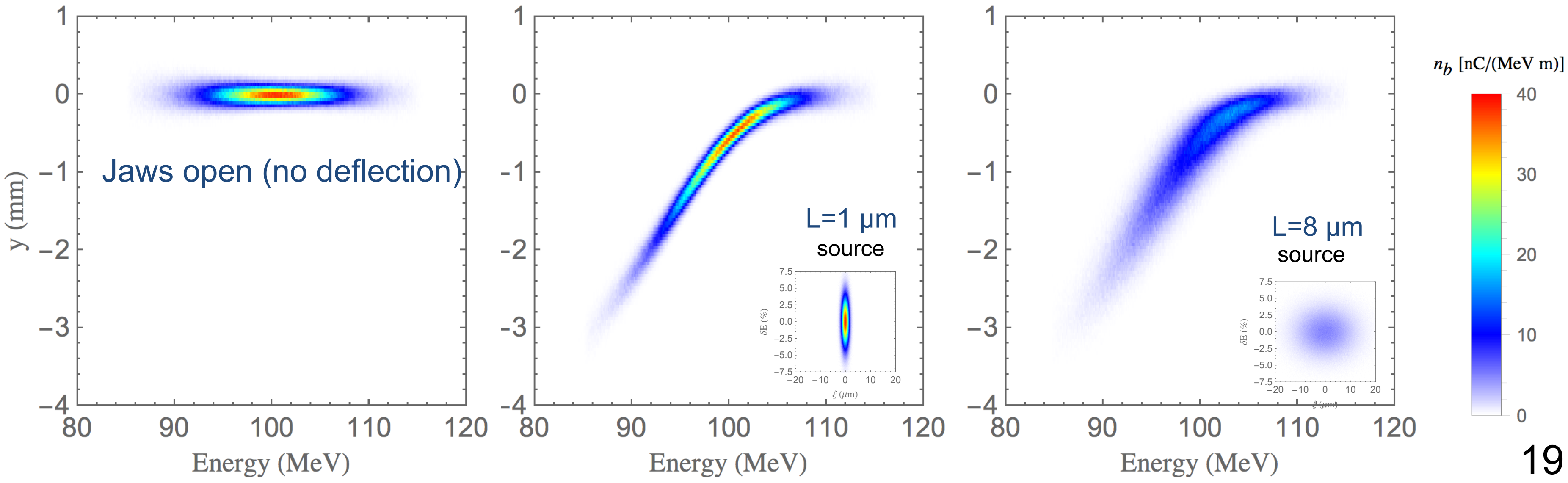


Incorporation of a high-resolution setup to measure energy- & time-sliced properties

Bettoni *et al.* PRAB 2016, Bane *et al.* PRAB 2016



Energy resolved deflected beams



Summary

- FEL-dedicated 100TW-driven LPA under development
- Laser near complete, LPA line in preparation
- Start-to-end simulations including collective effects
- FEL gain from 100-MeV e-beams well within reach
- Transport is designed to scale to higher energies (guided by LPA performance)
- Tilted jet – blade developed: stable, tunable e-beams
- First-of-kind LPA emittance parameter scans performed: down-ramp favorable to ionization injection
- Pros and cons of APLs under investigation