A Compact Laser-Plasma-Accelerator Free Electron Laser

Jeroen van Tilborg, BELLA Center

Lawrence Berkeley National Laboratory

Facet-II Science Workshop

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Contributors

PI: Jeroen van Tilborg

Experimental team:
- Core FEL team: **Sam Barber, Fumika Isono**, **Jeroen van Tilborg**
- BELLA contributors: Tony Gonsalves, Kei Nakamura, Sven Steinke, Jianhui Bin

- Senior support staff:
  Carl Schroeder, Wim Leemans*, Cameron Geddes, Eric Esarey

Collaborators:
- UCLA: Nathan Majernik, Jamie Rosenzweig
- Ohio State University (OSU): Anthony Zingdale, Nicholas Czapla, Douglass Schumacher

Funding
- Department of Energy, Basic Energy Sciences (BES):
- Department of Energy, High Energy Physics (HEP):
- Gordon and Betty Moore Foundation: equipment grant

Fumika Isono
UC Berkeley grad student

Sam Barber
Post-doc

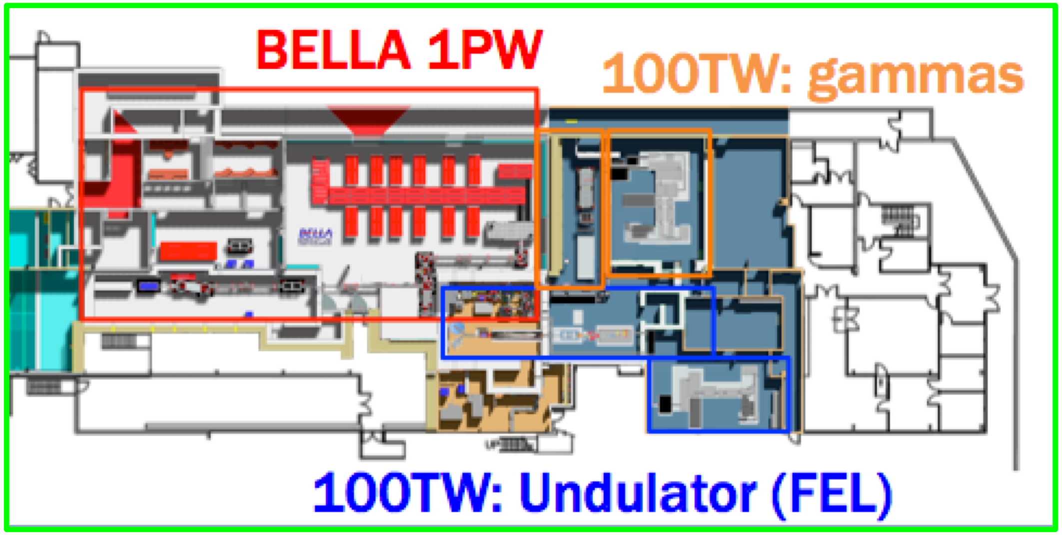
*Currently at DESY

Outline

LPA FEL: concept, simulations, experimental lay-out

Where are we now? update on laser system, beam-line, LPA source, transport & emittance diagnostics, undulator commissioning, upcoming experiments

FEL-relevant advanced accelerator concepts at the BELLA Center
- Common-path plasma density diagnostic
- Compact multi-GeV high-res spectrometer & emittance diagnostic
- Observation of near-field COTR interference

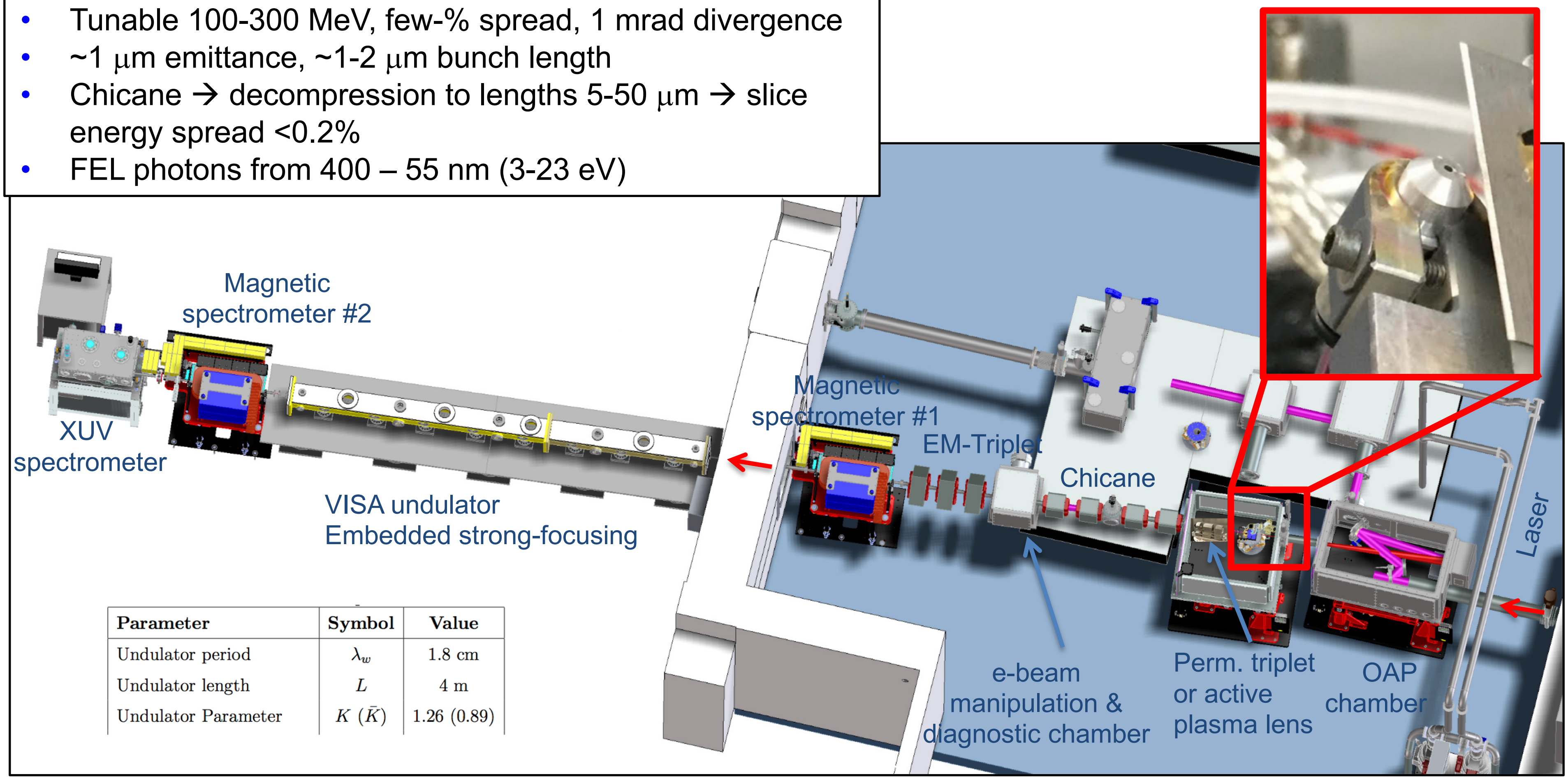


Tunable FEL in UV to soft X-ray domain demands excellent beam quality and tailored beam transport line

Multi-TW laser system → LPA source → Rapid e-beam collimation → Phase-space manipulation → Transport to undulator → Undulator

BELLA Center LPA FEL:

- Tunable 100-300 MeV, few-% spread, 1 mrad divergence
- ~1 μm emittance, ~1-2 μm bunch length
- Chicane → decompression to lengths 5-50 μm → slice energy spread <0.2%
- FEL photons from 400 – 55 nm (3-23 eV)



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

Front-to-end simulations in phase-1 (100 MeV → ϕ @ 3 eV) and phase-2 (300 MeV → ϕ @ 23 eV) validate LPA FEL concept

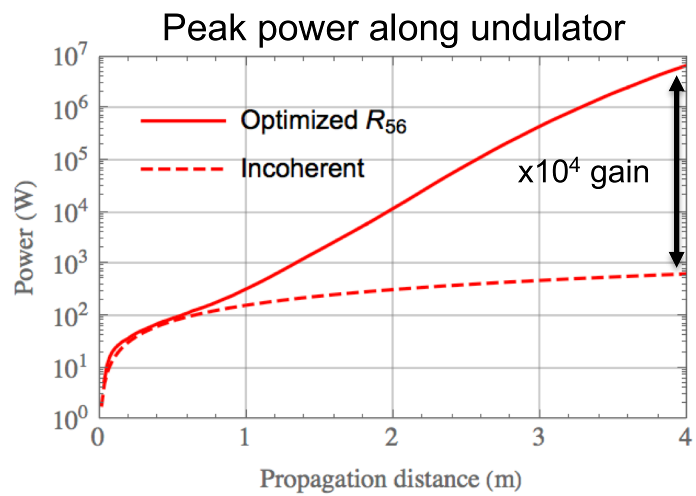
Extensive front-to-end simulations performed, including collective effects (space charge & coherent synchrotron radiation)

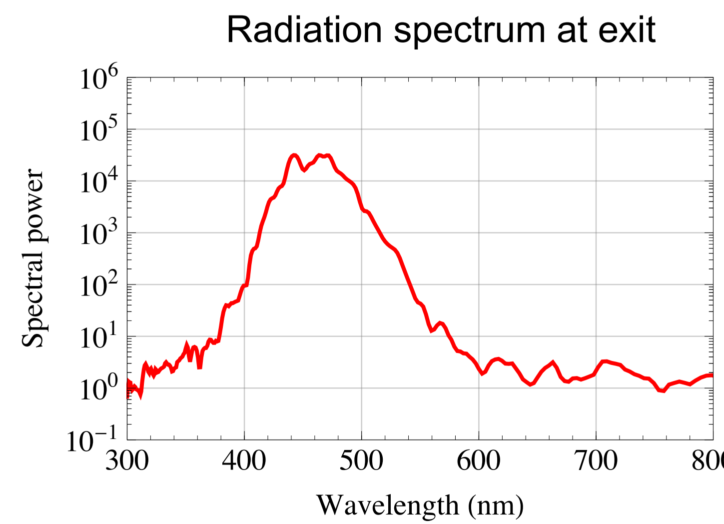
Codes: ELEGANT, ASTRA & GENESIS M. Borland LS-287 (2000), S. Reiche NIMA 429 (1999).

Phase-1

LPA source:

- 100 MeV
- 25 pC
- $\sigma_\gamma = 2.5\%$
- $\varepsilon_n = 0.3\ \mu m$
- $\sigma_z = 1.0\ \mu m$
- λ_l=420 nm

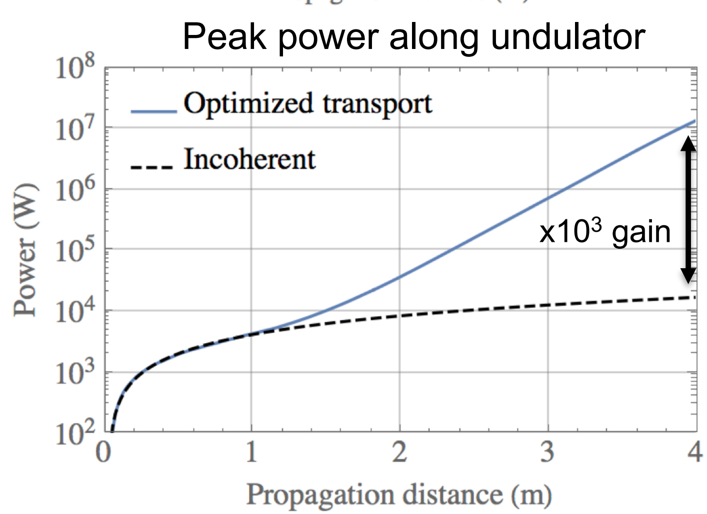


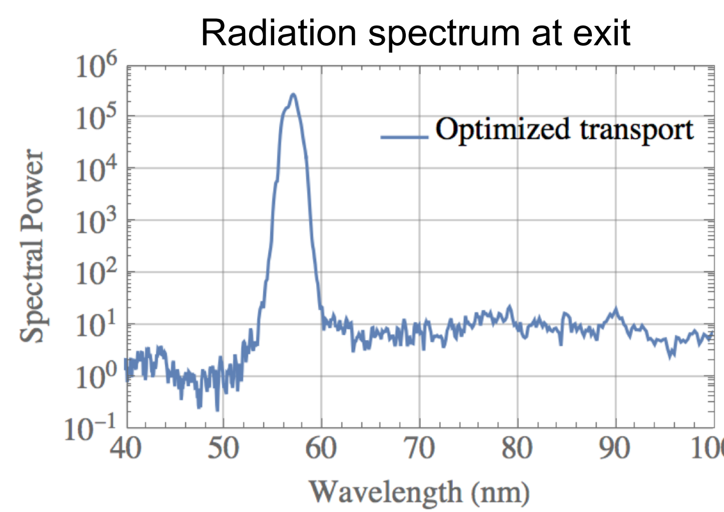


Phase-2

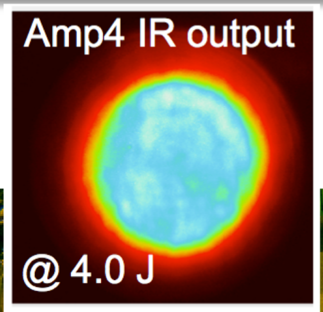
LPA source:

- 275 MeV
- 25 pC
- $\sigma_\gamma = 1.0\%$
- $\varepsilon_n = 0.3\ \mu m$
- $\sigma_z = 1.0\ \mu m$
- λ_l=55 nm (23 eV)

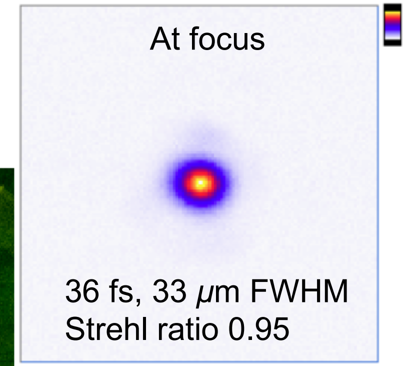


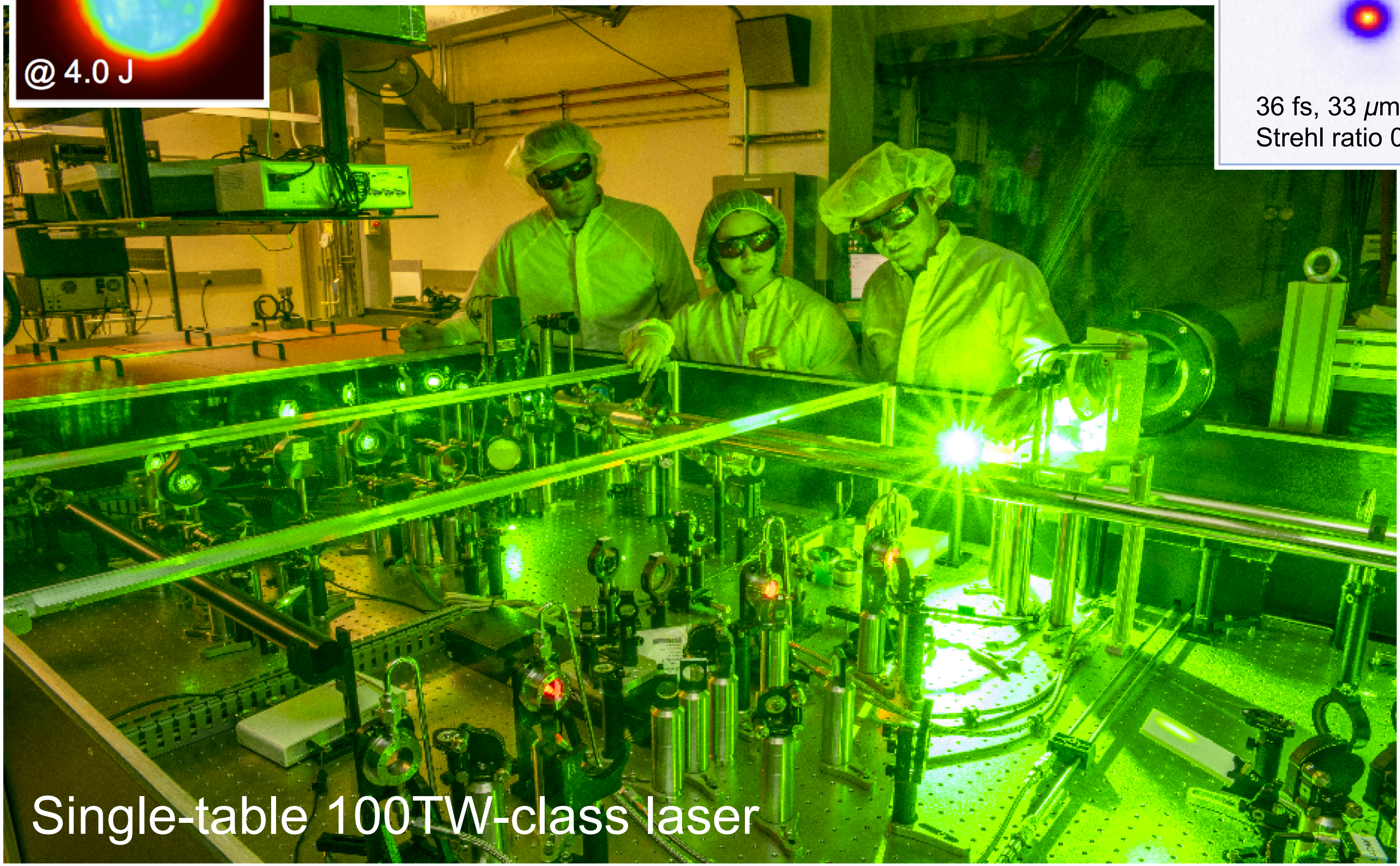


Project start in 2016. 5 Hz laser operational since 2018. Single-table system. One pump laser, home-built amplifier chain

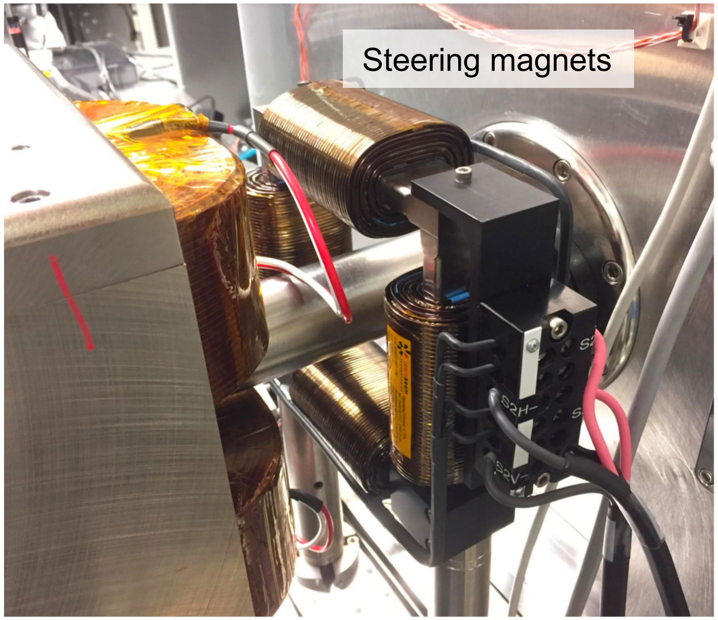


2018: laser commissioned!
4 Joule (2.5J on target)

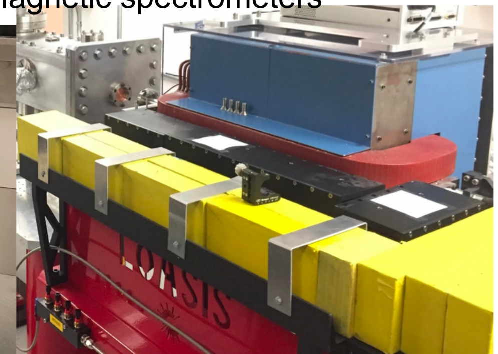


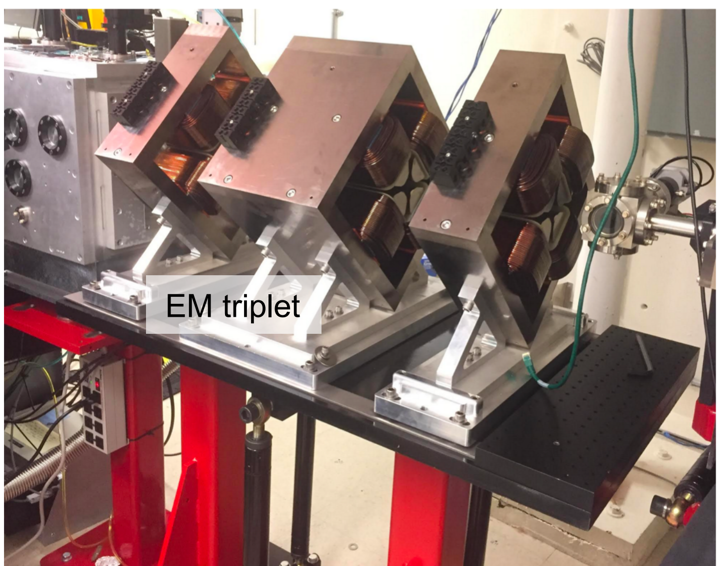


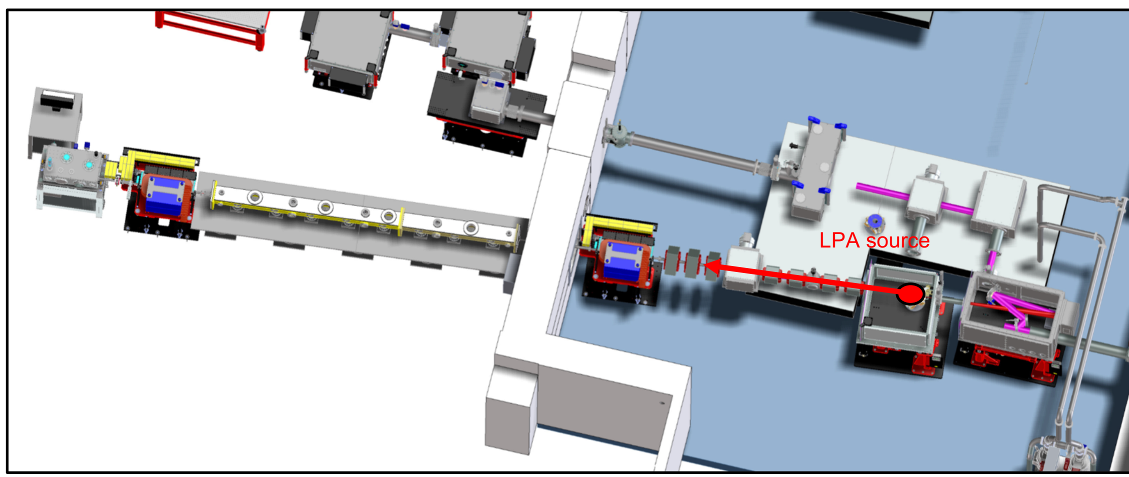
Beamline: chambers, permanent triplet, EM triplet, two magnetic spectrometers, and EM steering magnets installed



Magnetic spectrometers







EM chicane (R56~1mm) installed with UCLA collaboration. Unique for LPA: compact, large area of uniform B-field

PHYSICAL REVIEW ACCELERATORS AND BEAMS **22**, 032401 (2019)

Optimization of low aspect ratio, iron dominated dipole magnets

N. Majernik,[1,2,*] S. K. Barber,[2] J. van Tilborg,[2] J. B. Rosenzweig,[1] and W. P. Leemans[2,3]
[1]*University of California—Los Angeles, Los Angeles, California 90095, USA*
[2]*Lawrence Berkeley National Lab, Berkeley, California 94720, USA*
[3]*Deutsches Elektronen Synchrotron DESY, 22607 Hamburg, Germany*

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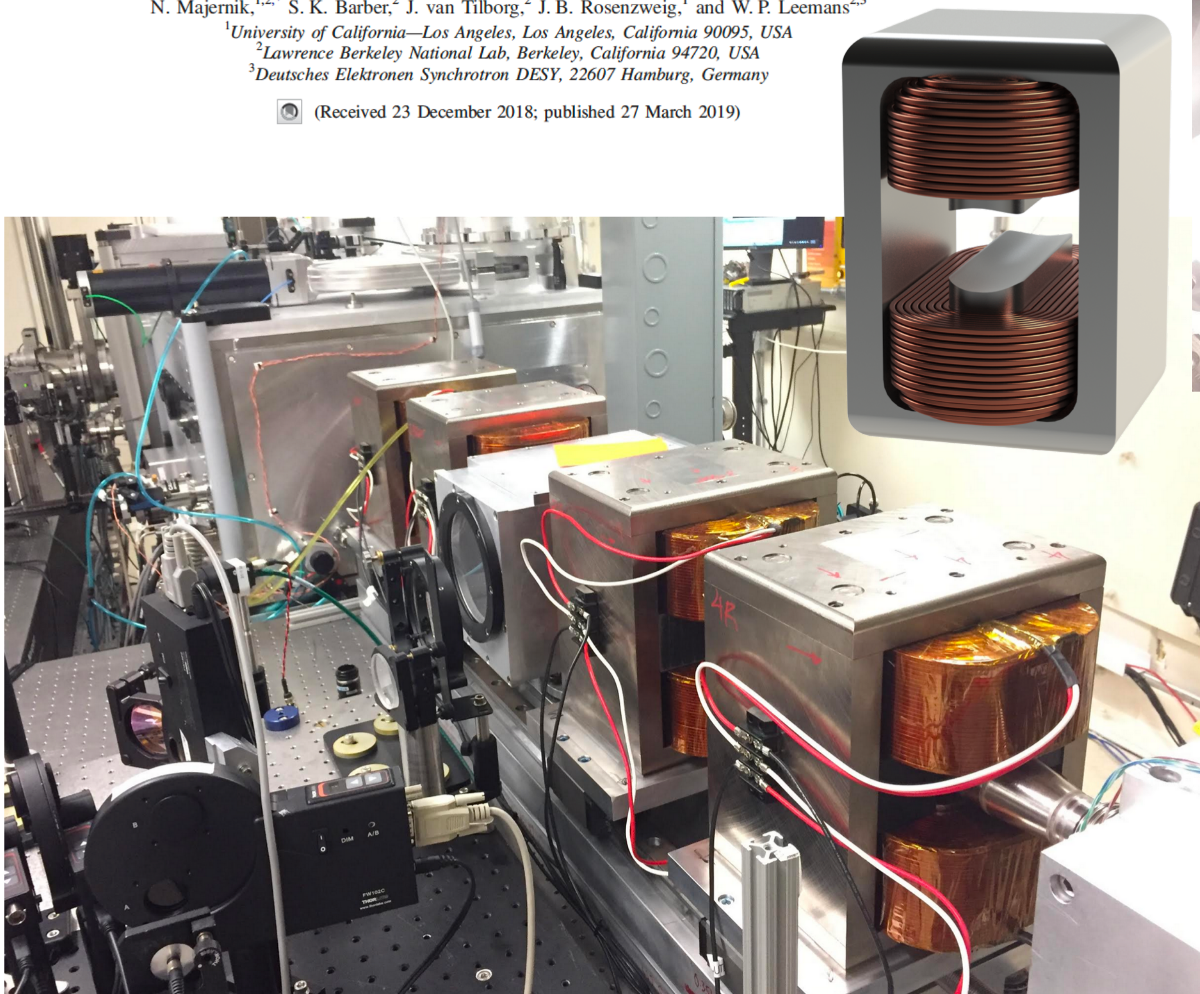
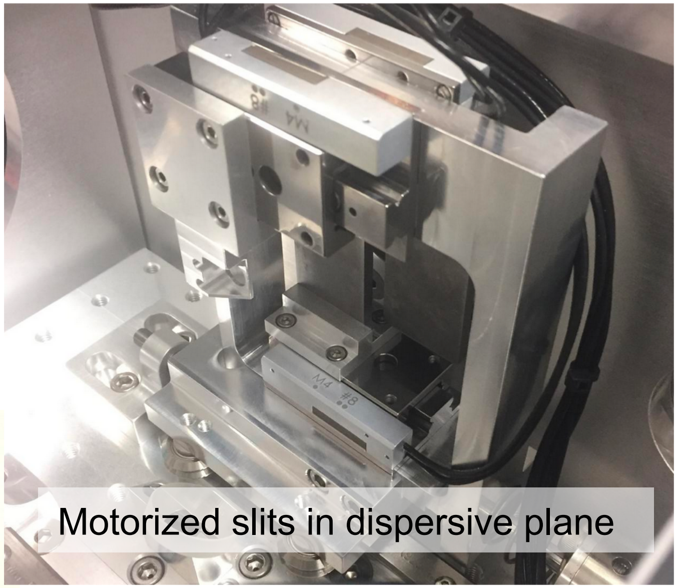
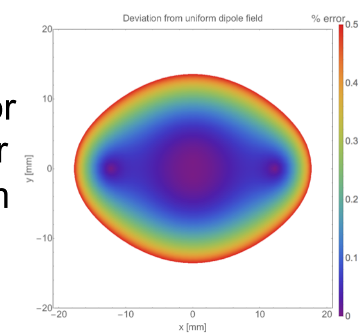
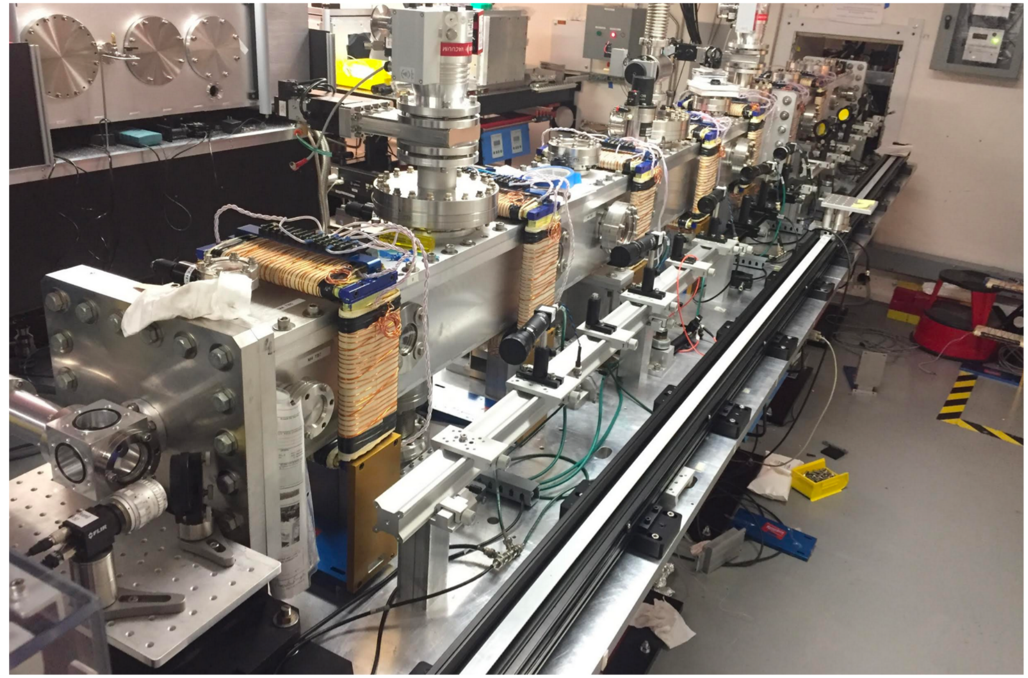


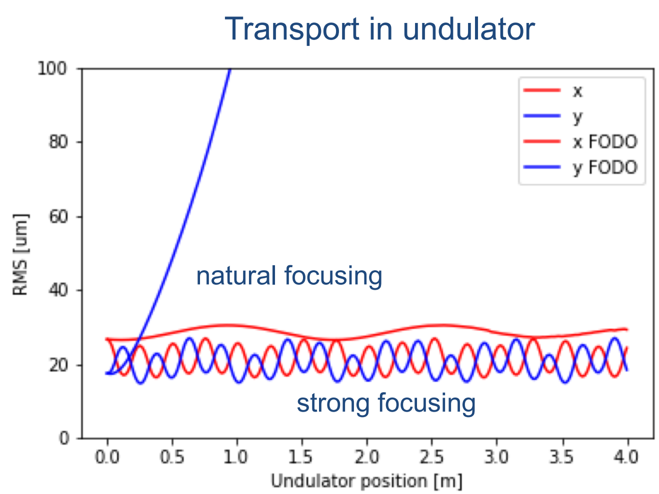


Field error <<1 % for 10x10mm area



4-meter long VISA undulator installed on beam line. Strong-focusing undulator with 4 sections and 4 FODO cells per section.





Parameter	Symbol	Value
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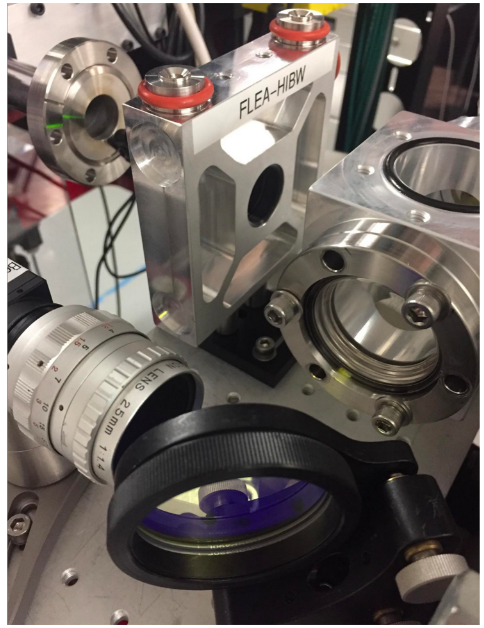
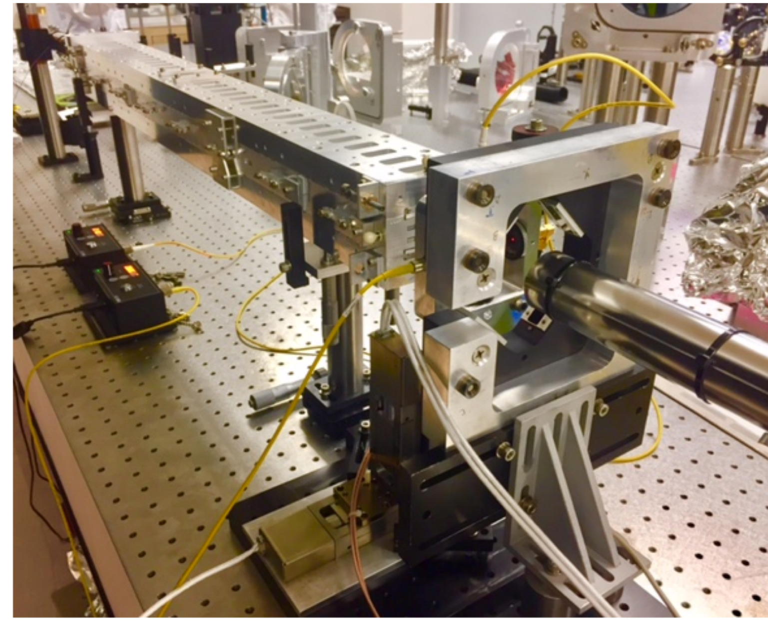
VISA undulator:
Carr *et al.* PR-STAB 2001
Murokh *et al.* PRA 2003
FEL operation at ATF:
Frigola NIMA (2001),
Tremaine PRL 88, 204801 (2002)

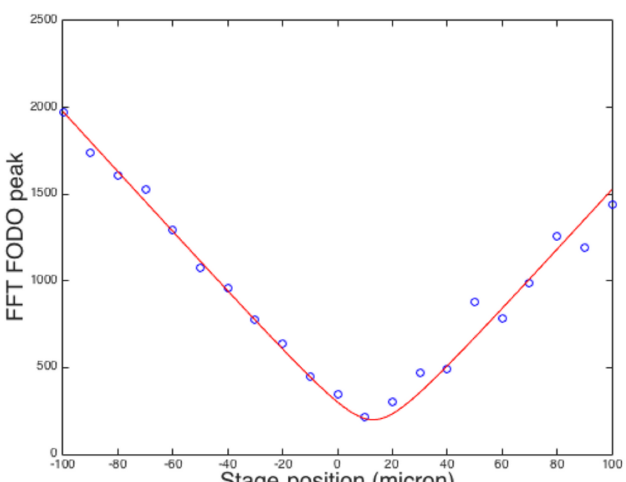
Each 1-meter section magnetically characterized on a pulsed-wire system, then fiducialized, now installed

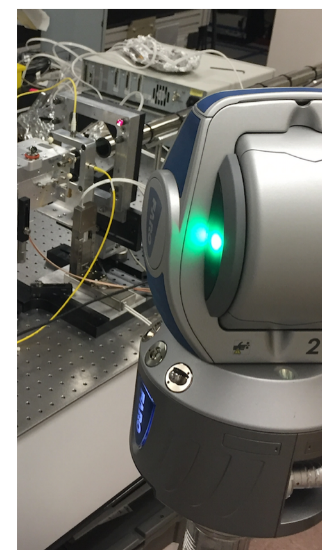
Each segment:

- Magnetic axis found with pulse wire system
- Permanent fiducials added to segment frame
- ALS Survey Group: fiducialization at <20 μm (not available 20 years ago)
- Wire position (“magnetic axis”) recorded with respect to undulator fiducials
- Through fiducialized CCD cameras, magnetic axis transferred to beam profile monitors
- All segments installed & aligned

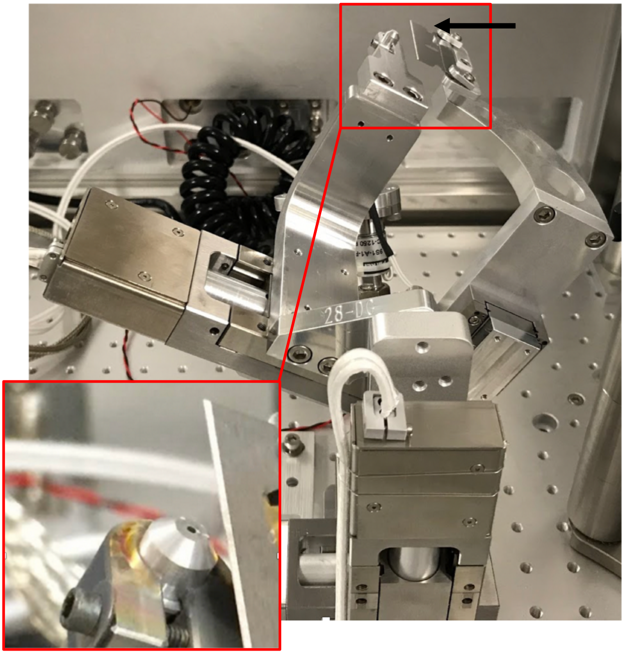




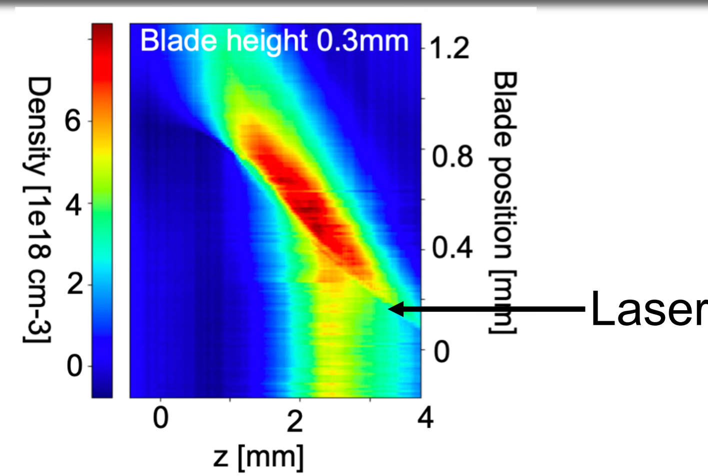




Jet-Blade installed, density characterization performed. For now: LPA beams from ionization injection

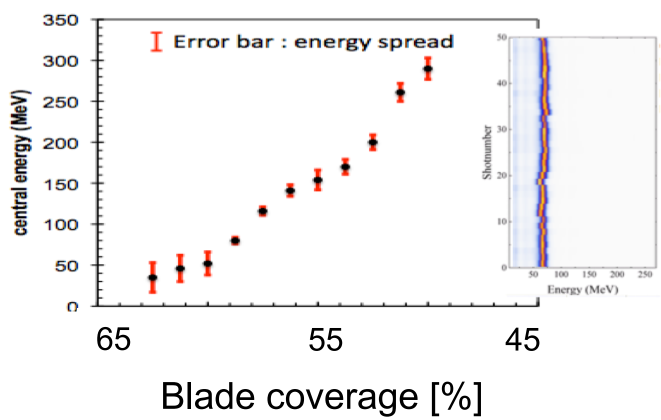


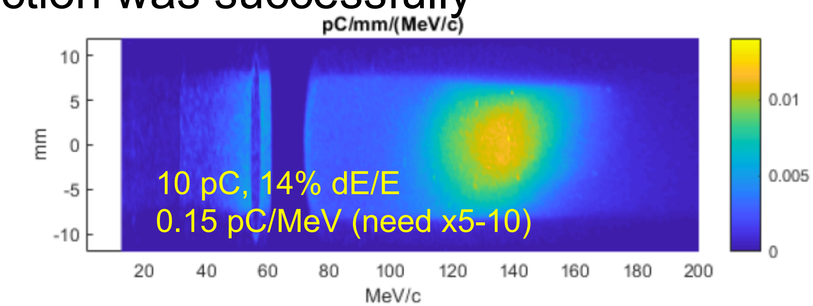
Gas jet with blade on 5-axis stage (blade overlap jet & blade height to jet)



Jet-blade on-line density characterization completed, accelerator to be tested soon

In the mean time (commissioning phase), ionization injection was successfully demonstrated



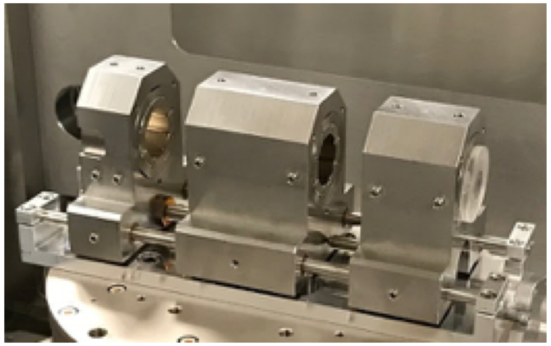


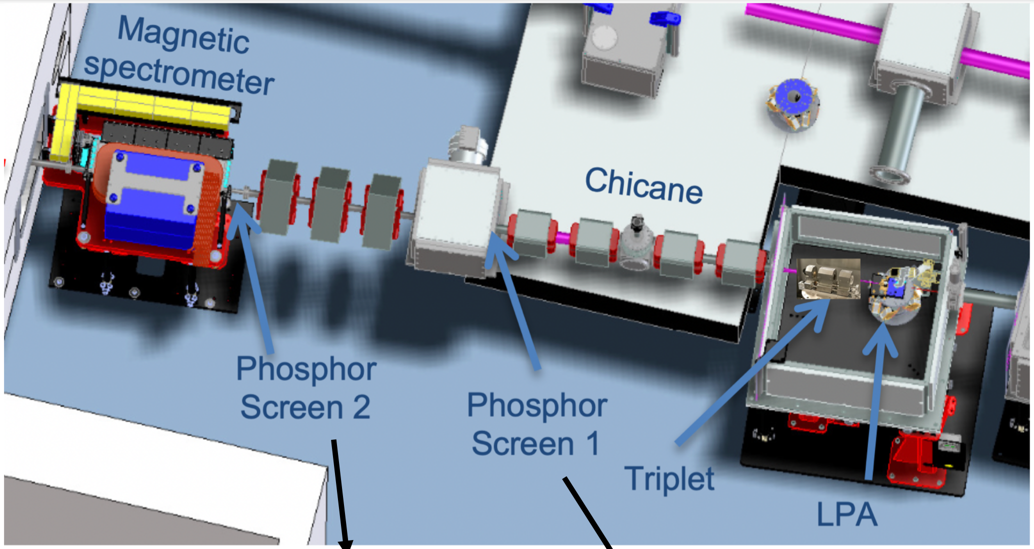
Fall 2018: First e-beams!

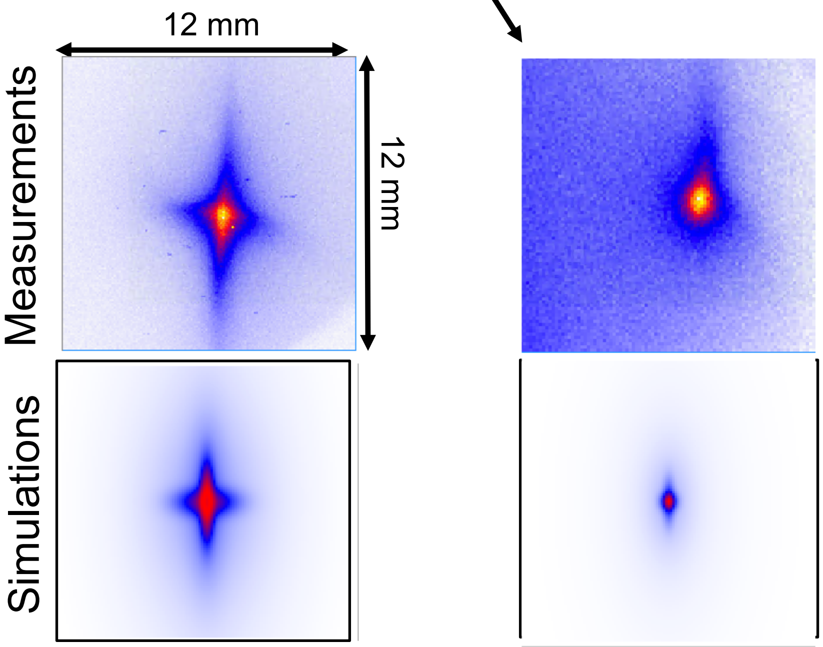
Down ramp injection:
Bulanov PRE (1998), Suk PRL (2001), Geddes PRL (2008), Gonsalves Nature (2011), Schmid PRL (2010), **Swanson PR-AB (2017), Tsai Phys. Plasmas (2018)**

Characterization of the e-beam transport is benchmarked against simulation

50-80 MeV triplet on loan from RadiaBeam (see Fedurin IPAC 2012)

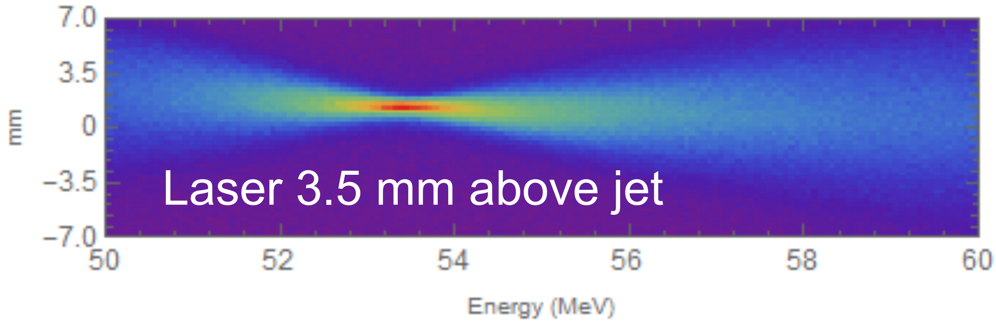


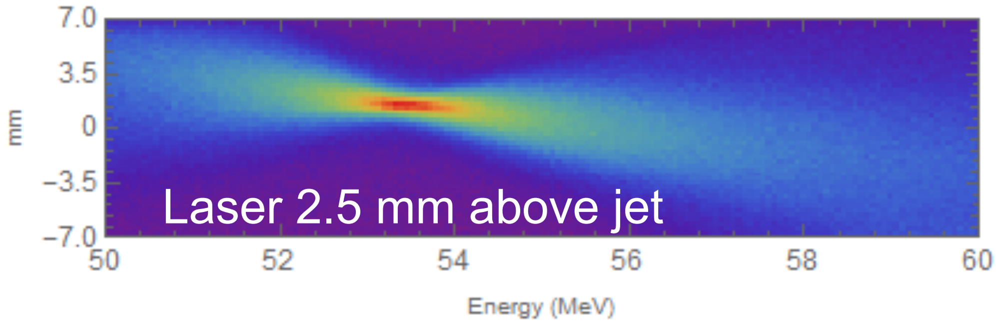


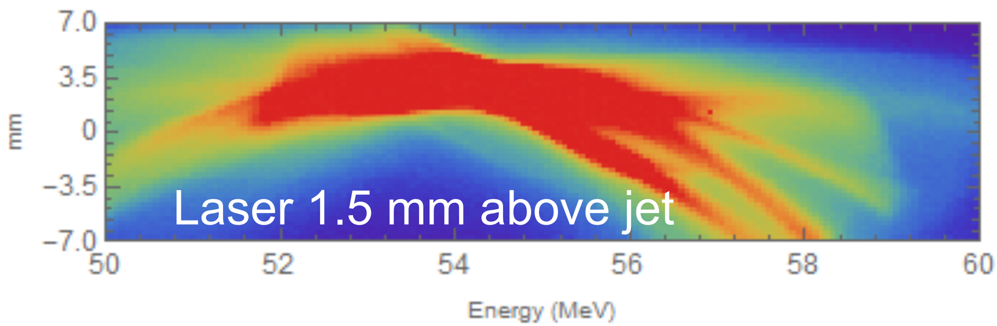


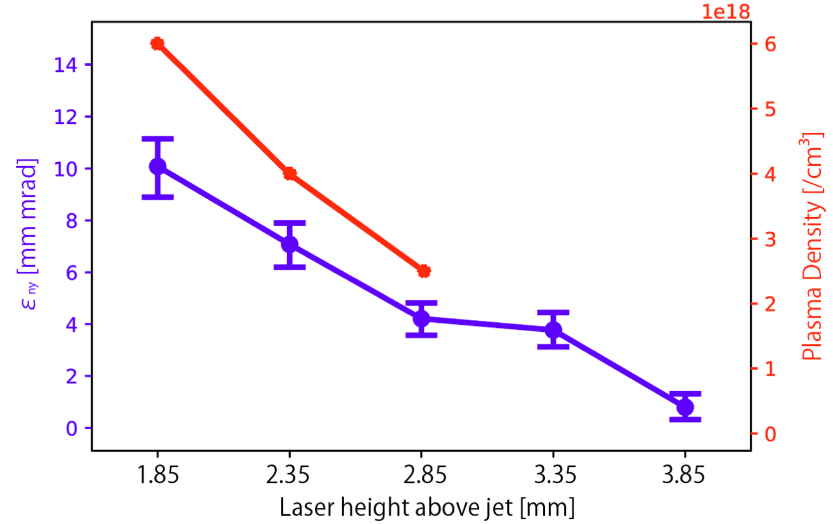
Brightness (ratio charge/emittance) optimization underway

Laser focus height relative to jet exit is adjusted:









Near-term goals

- Optimize LPA
- Apply chicane to phase-space manipulation
- Commission undulator diagnostics
- First light from undulator

Single-shot LPA emittance: Weingartner *et al.* PRSTAB (2012), Barber *et al.* PRL (2017)

Outline

LPA FEL: concept, simulations, experimental lay-out

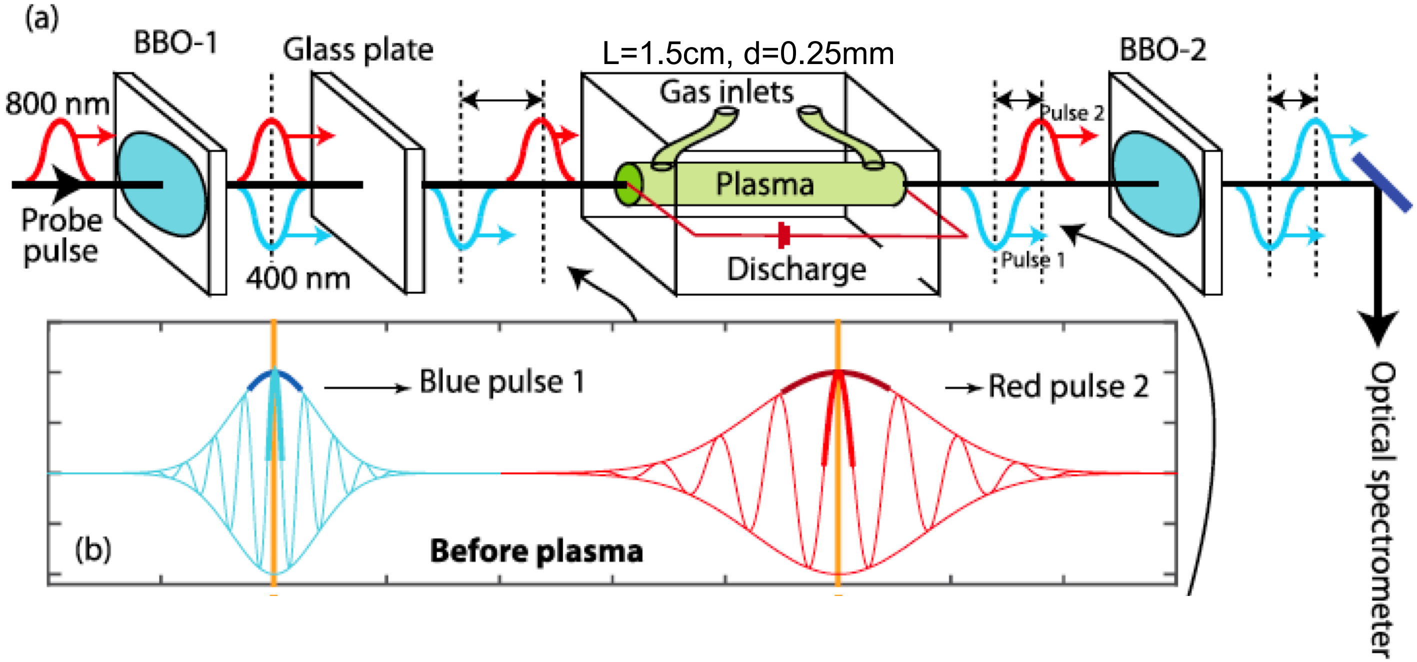
Where are we now? update on laser system, beam-line, LPA source, transport & emittance diagnostics, undulator commissioning, upcoming experiments

FEL-relevant advanced accelerator concepts at the BELLA Center

- Common-path plasma density diagnostic
- Compact multi-GeV compact high-res spectrometer & emittance diagnostic
- Observation of near-field COTR interference

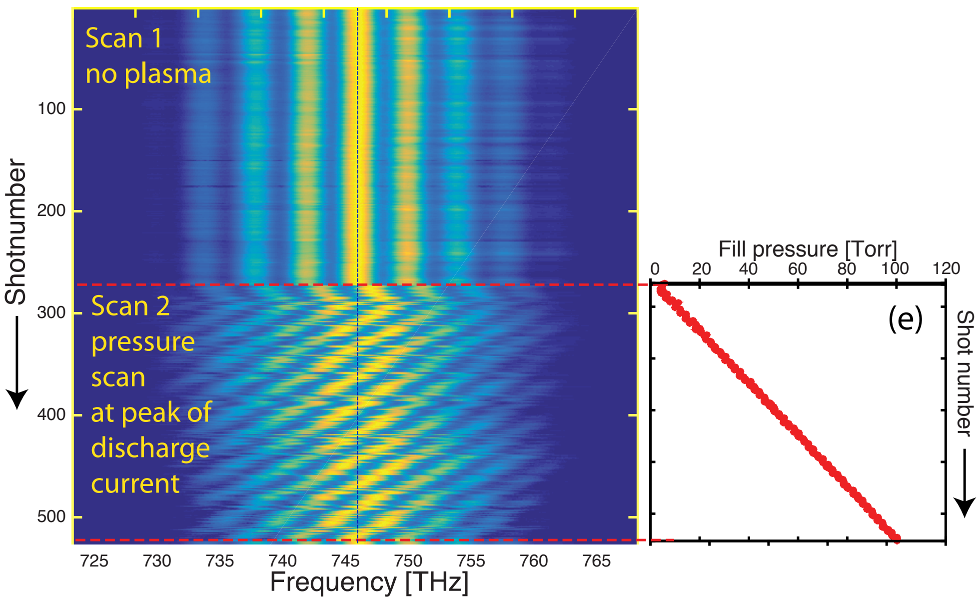
Plasma density diagnostic: common-path non-linear interferometry with femtosecond laser pulses

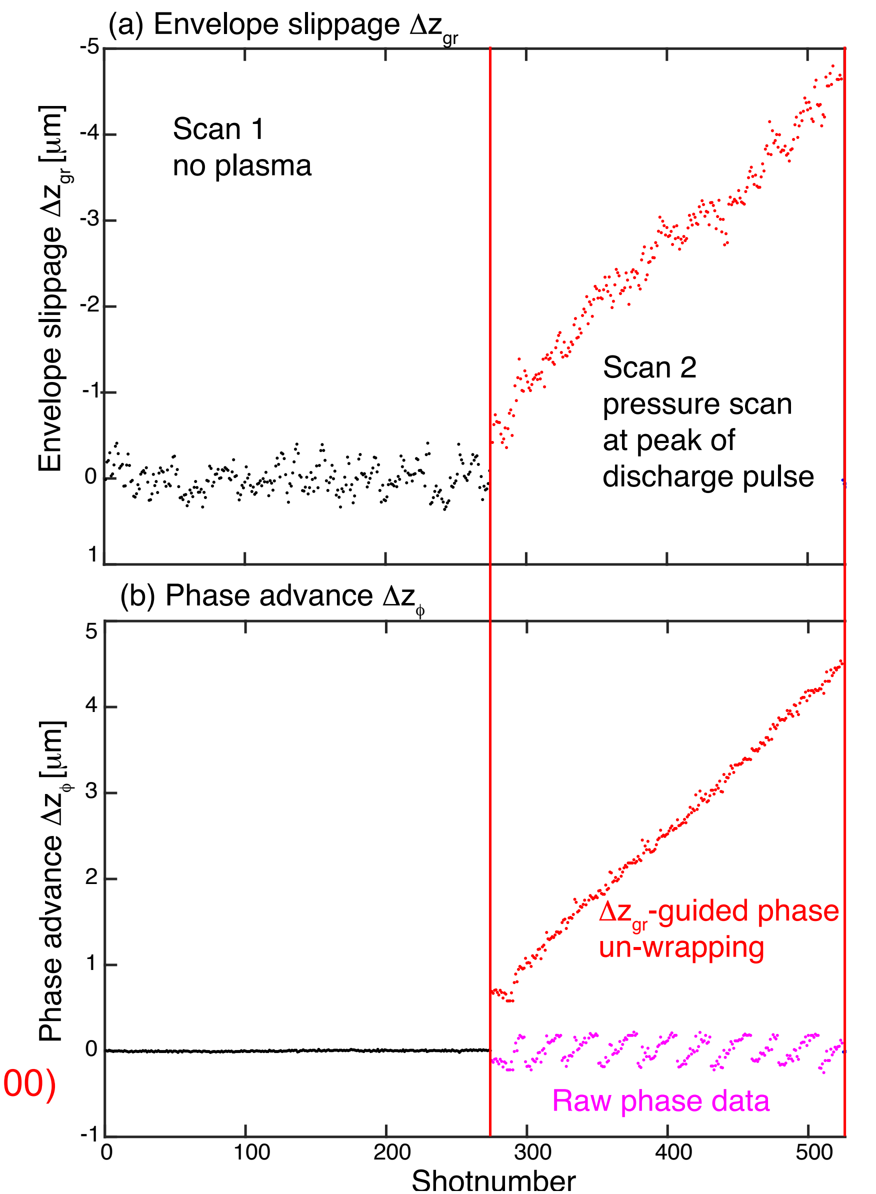
van Tilborg et al. Physics of Plasmas **26**, 023106 (2019)



Common-path

Absolute phase retrieval: (1) phase tracking in slowly varying scan, or (2) group velocity. Sensitivity for density x length = 1.8×10^{15} cm^{-2}





Standard deviation Group Velocity Delay (GVD) = 181 nm
Standard deviation Phase Velocity Advance = 4.0 nm (λ_{blue}/100)
Density-length product sensitivity of 1.8×10^{15} cm^{-2}
For example: L=10cm → sensitivity in n=1.8×10^{14} cm^{-3}

van Tilborg et al. Physics of Plasmas **26**, 023106 (2019)

Active Plasma Lens implemented as compact e-beam diagnostic on BELLA PW multi-GeV LPA

- Conventional magnets challenging in multi-GeV compact transport
- Approach: active plasma lenses (APLs), well described in recent years

Panofski RSI (1950), van Tilborg PRL (2015), Pompili APL (2017), van Tilborg Phys. Plasmas (2017), van Tilborg PR-AB (2018), Pompili PRL (2018), Lindstrom PRL (2018)

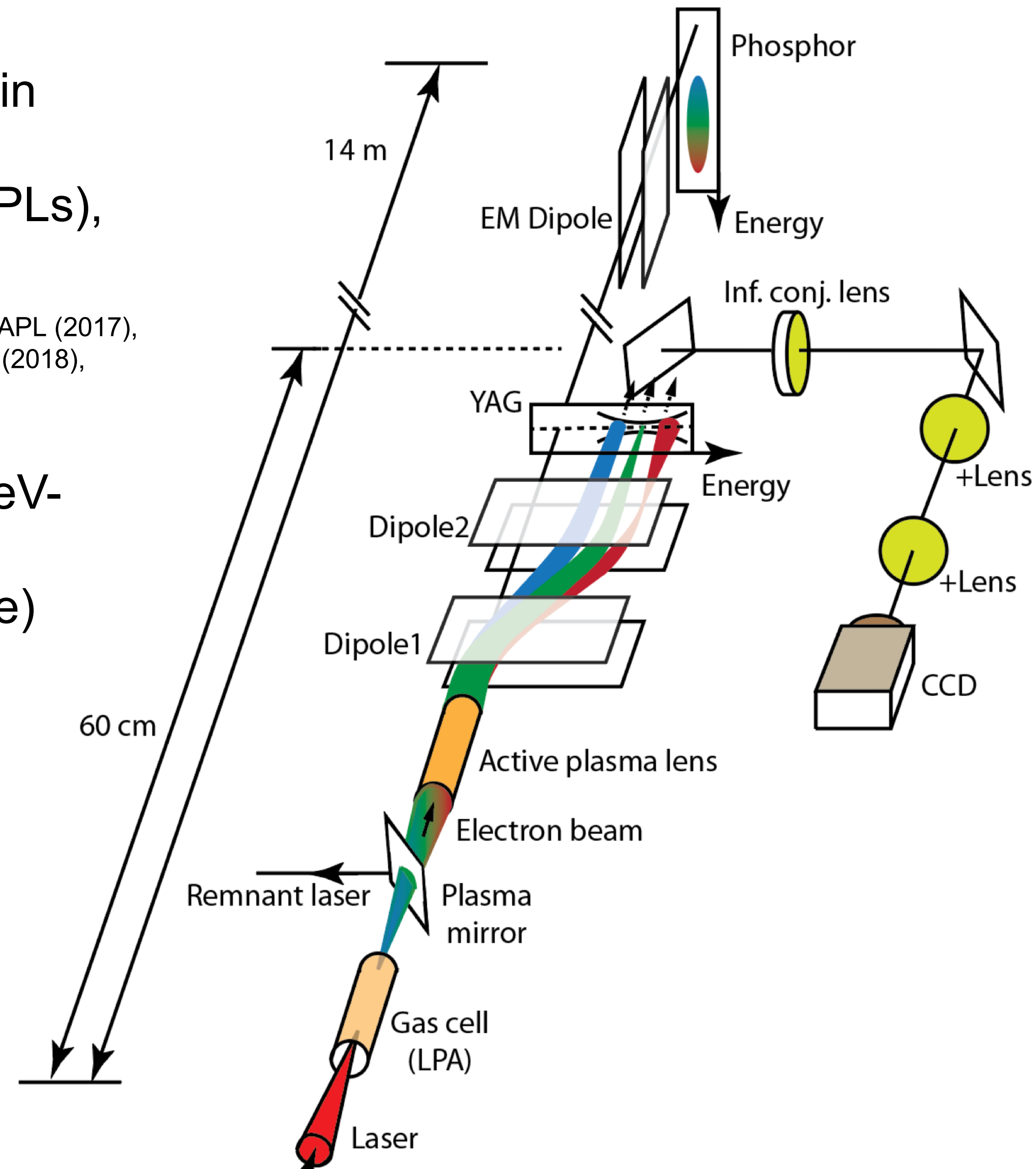
How about APLs towards **compact** GeV-class beam diagnostics?
(electron energy distribution, emittance)

Magnetic spectrometers governed by:

$$\sigma_x = \sqrt{\frac{\beta_x \epsilon_{nx}}{\gamma_0} + \left(\eta_x \frac{\delta\gamma}{\gamma_0}\right)^2}$$

Can be very small with short focal length APL

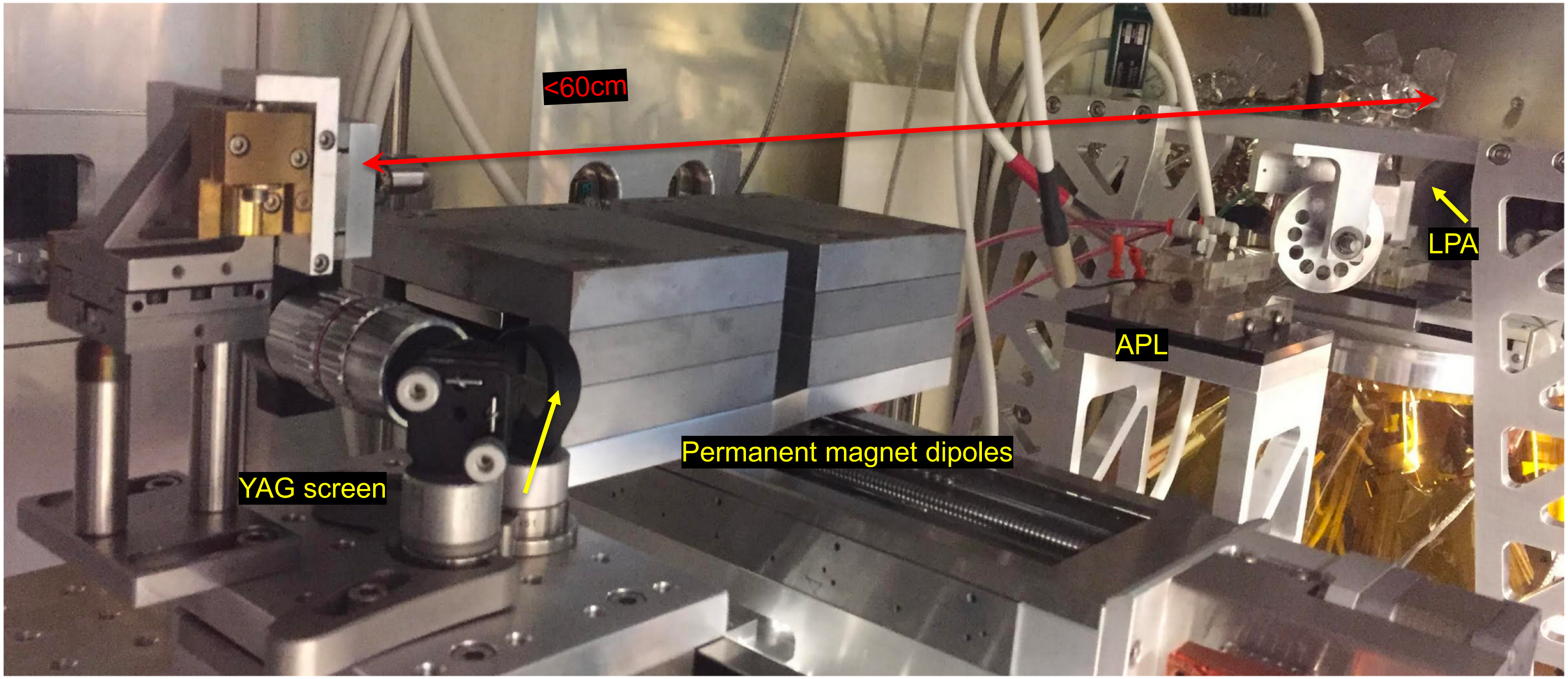
Must be dominant term for magnetic spectrometer



S. Barber, J. van Tilborg et al. in preparation

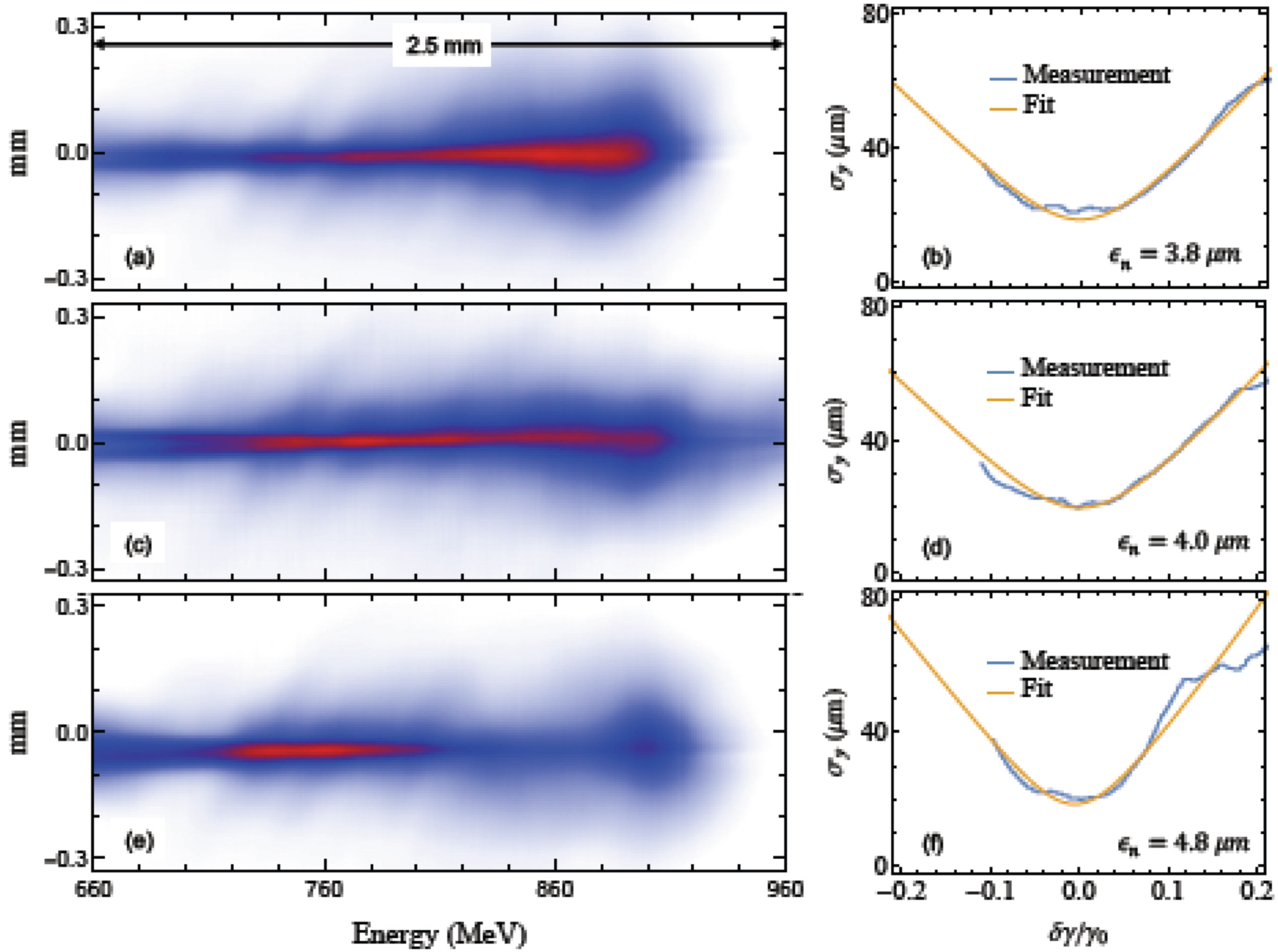
Compact high-resolution magnetic spectrometer realized by coupling APL focusing to dipole magnet

- Two 10 cm long, 0.9T dipoles in dogleg configuration provide dispersion, minimize impact on radiation safety
- Liquid crystal film protects APL (20 nm thickness) D. Schumacher's OSU team
- <1% energy resolution for electrons up to 2 GeV when using F<20cm APL
- Can simultaneously be used for emittance measurement
- Scalable to 10 GeV



S. Barber, J. van Tilborg et al. in preparation

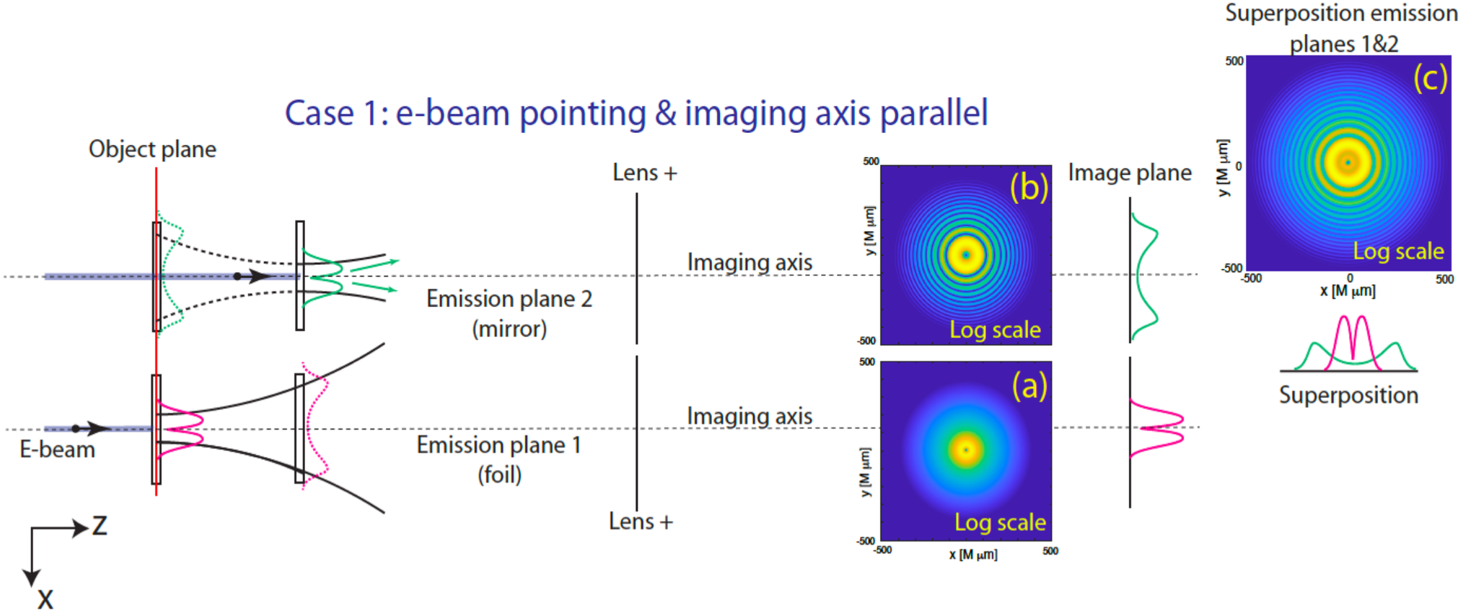
Single-shot compact energy distribution & emittance diagnostic demonstrated at 0.5-1.5 GeV (0.8 GeV shown here)

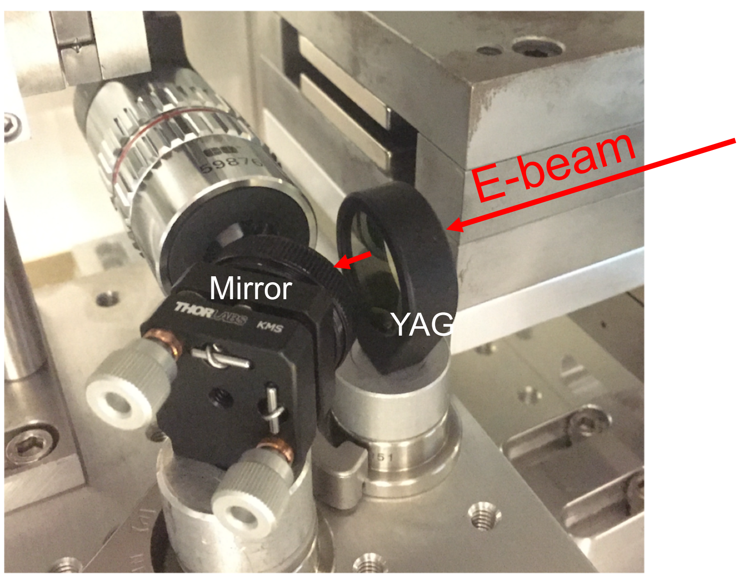


S. Barber, J. van Tilborg et al. in preparation

APL: 0.5 mm diameter, 6 cm length, 100 A discharge ~15 cm focal length at 1 GeV

Typical high-resolution OTR setup: OTR from two surfaces collected. 5-μm-size LPA beams → near-field coherent Wartski interferometer



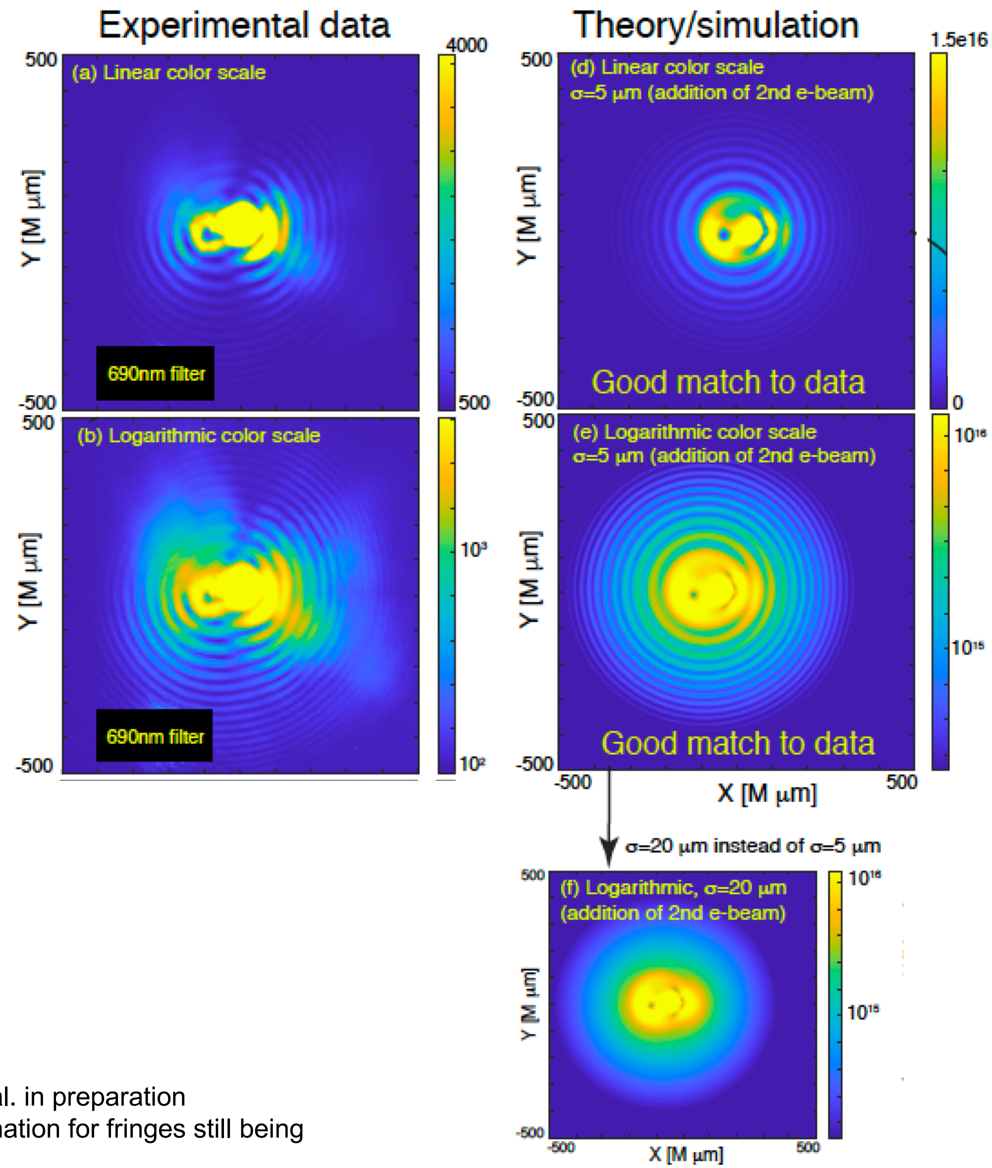


Theory based on Castellano PRSTAB (1998)

In-depth communication with UT-Austin/Fermilab/Dresden team (Max Laberge, Mike Downer, Alex Lumpkin, et al.)

Recent far-field Wartski LPA COTR in Lumpkin et al, arxiv.org/abs/1812.10778

Experimental data agrees with simulations. COTR interference could impact tightly-focused beam diagnostics.



J. van Tilborg et al. in preparation
Alternative explanation for fringes still being investigated.

Summary

LPA & transport optimization in progress, ionization & down-ramp injection pursued.

BELLA Center LPA FEL: hardware complete, including laser system, beam line, and undulator. Soon: beam into undulator.

Improved plasma density diagnostic developed

Active plasma lenses well-suited for compact high-res diagnostics (energy distribution, emittance). COTR (interference) affects beam diagnostics.