# Emergency Information



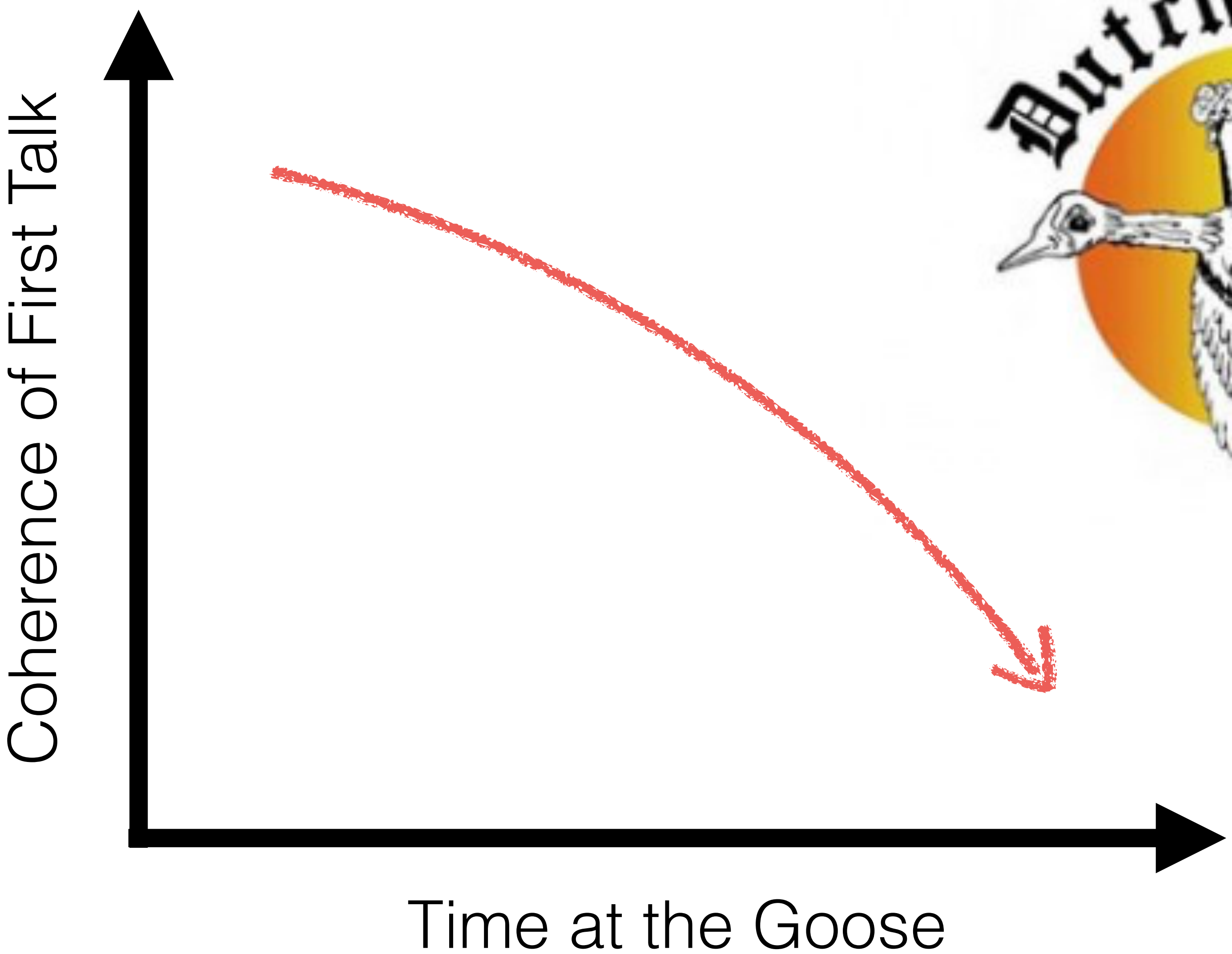
## Fire

- Evacuate. Be aware of building exits.
- Follow building residents to the assembly area.
- Do not leave until you are accounted for, and have been instructed to.

## Earthquake

- Remain in building: duck, cover, and hold position.
- When shaking stops: evacuate building via a safe route to the assembly area.
- Do not leave until you are accounted for, and have been instructed to do so.

# An Observation




FACET-II

Facility for Advanced Accelerator Experimental Tests

# FACET-II Science Workshop: Witness Injector Motivation & 100 MeV Option

FACET-II Science Workshop October 17-19, 2016

Mark J. Hogan

FACET-II Project Scientist

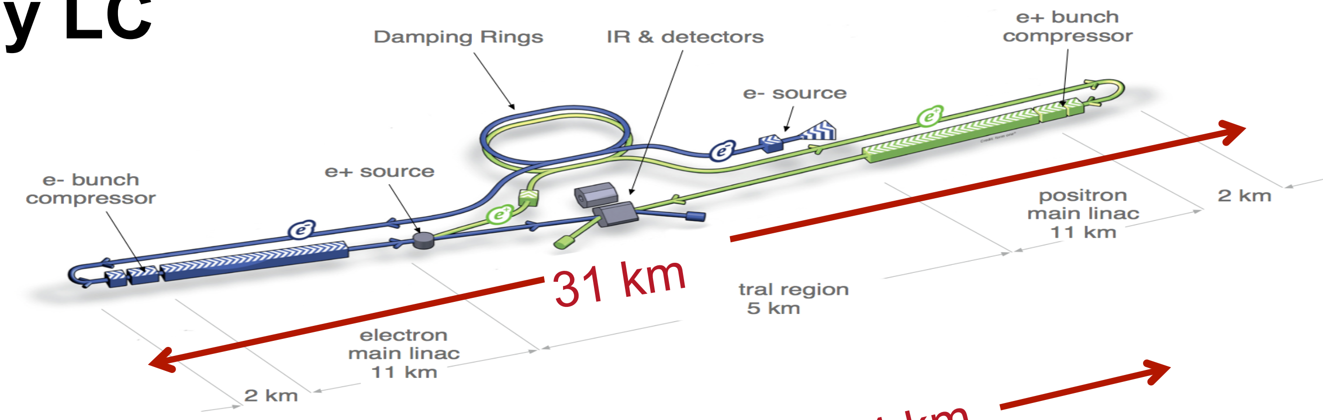
U.S. DEPARTMENT OF ENERGY

Office of Science

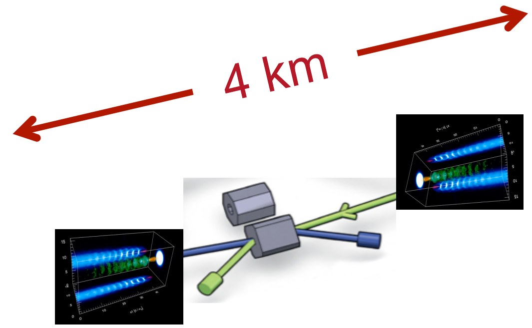
SLAC NATIONAL ACCELERATOR LABORATORY

# The Scale for a TeV Linear Collider

## Today's technology LC – a 31km tunnel:




## Plasma Wakefield Technology LC:




→ GeV/m accelerating gradient

## The Luminosity Challenge:

$$\mathcal{L} = \frac{P_b}{E_b}\left(\frac{N}{4\pi\sigma_x\sigma_y}\right)$$

→ High-efficiency

…and must do it for positrons too!

# PWFA Research Roadmap:
# Goal is to Get To A TeV Scale Collider for High Energy Physics

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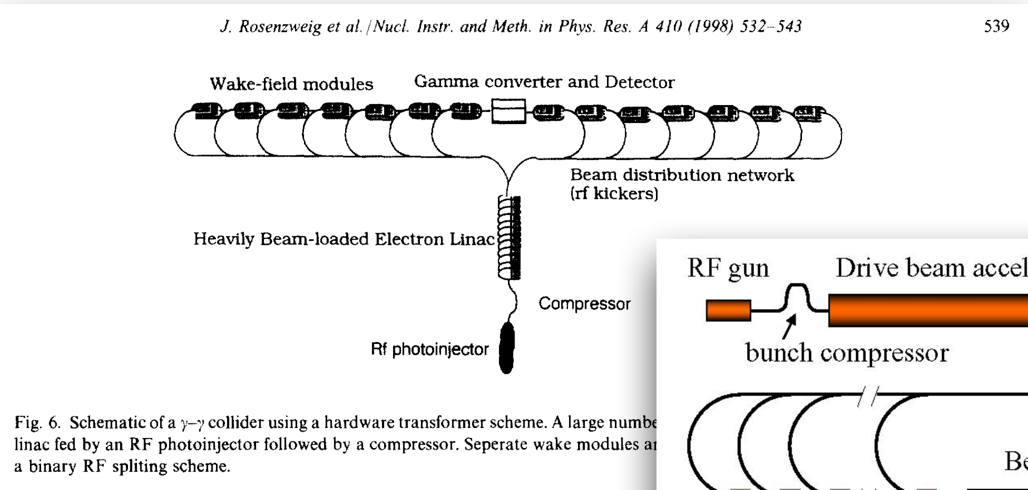
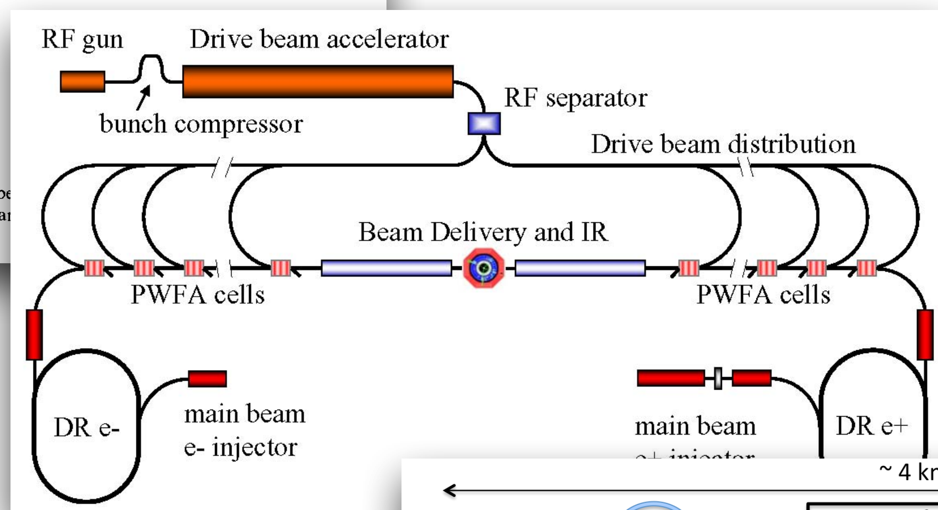
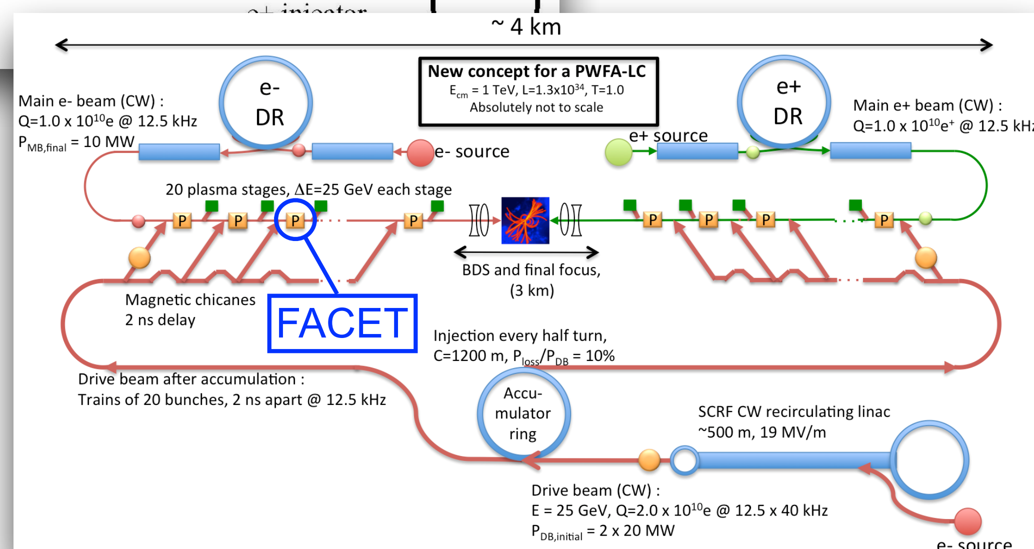



Rosenzweig *et al* (1998)



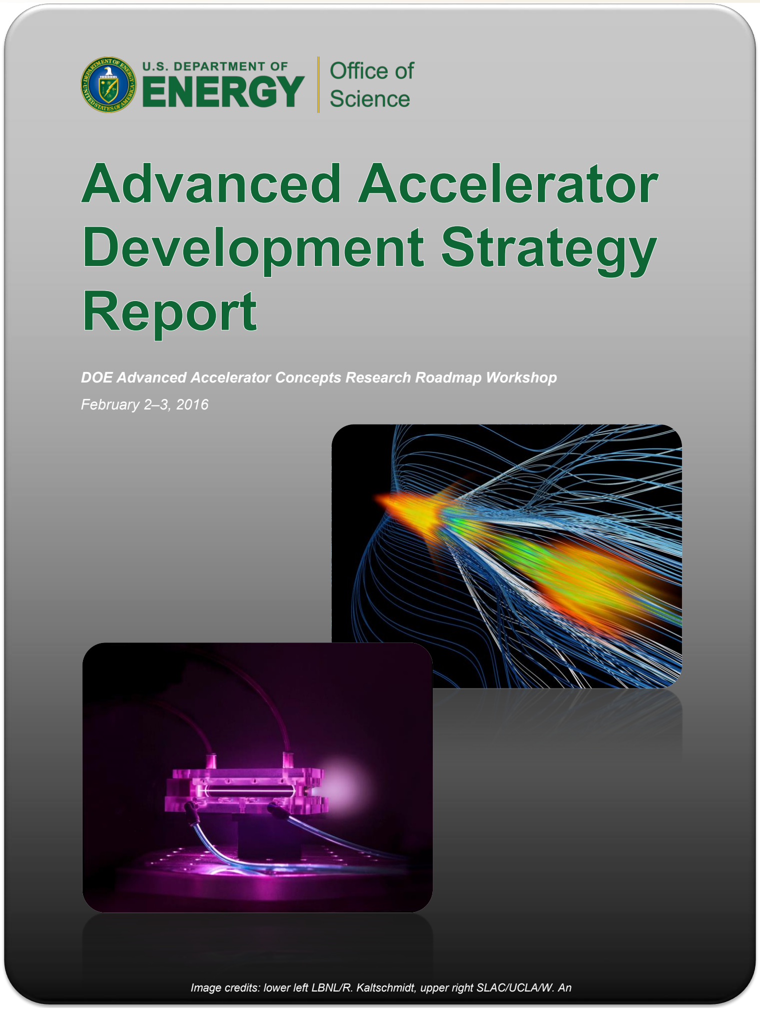

Seryi *et al* (2008)

Adli *et al* (2013)



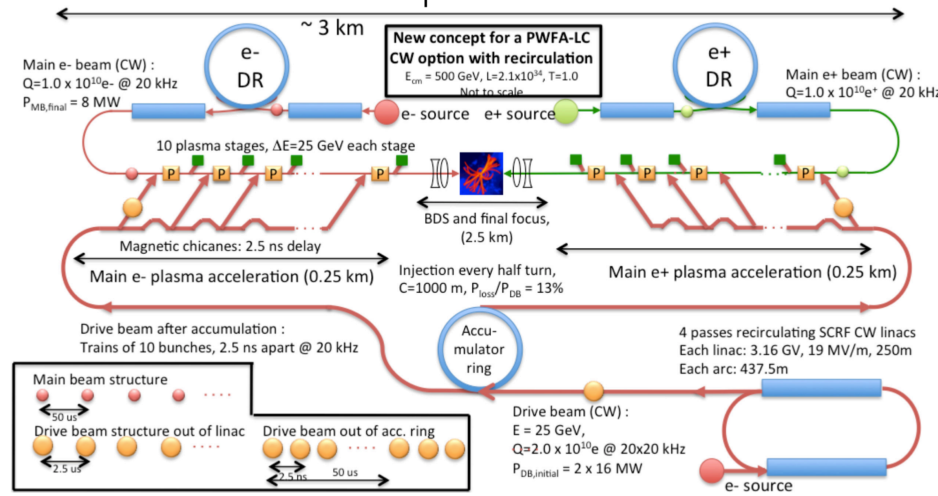

PWFA-LC concepts highlight key issues and help us prioritize our research programs e.g. efficiency, positrons

# A Roadmap for Future Colliders Based on Advanced Accelerators Contains Key Elements for Experiments and Motivates FACET-II




http://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Advanced_Accelerator_Development_Strategy_Report.pdf

A Conceptual PWFA-LC




E. Adli et al., ArXiv 1308.1145
J. P. Delahaye et al., Proceedings of IPAC2014

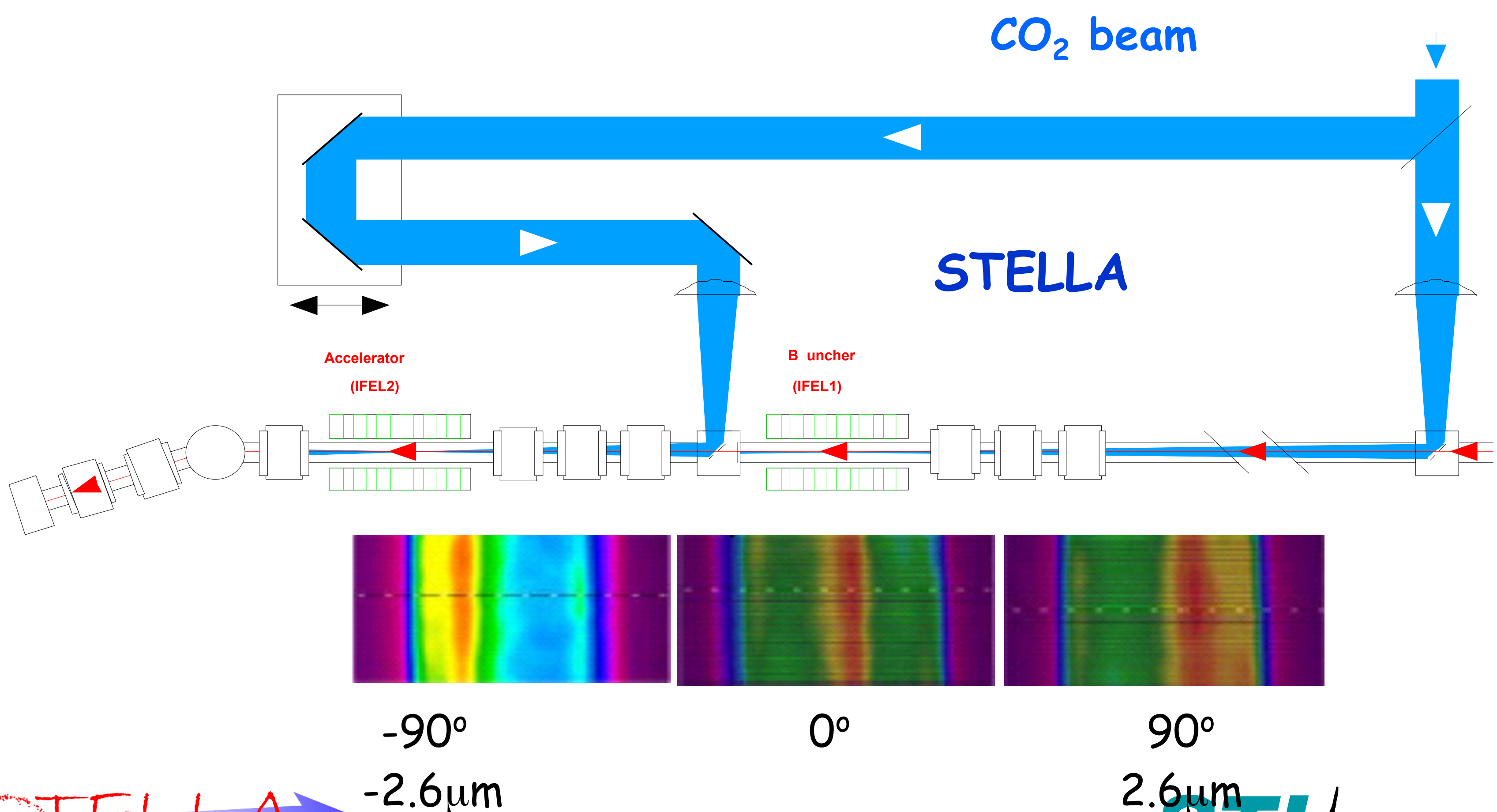
## Key Elements for PWFA over next decade:

- Beam quality – build on 9 GeV high-efficiency FACET results with focus on emittance
- Positrons – use FACET-II positron beam identify optimum regime for positron PWFA
- Injection – ultra-high brightness sources, staging studies with external injectors

# Schematic Layout of STELLA

STELLA, PRL **86**, 4041 (2001)

## First Staging of Two Laser Accelerators




STELLA
Staged Electron Laser Acceleration

STI OPTRONICS

STELLA
Staged Electron Laser Acceleration

# summary

- First demonstration of staging monoenergetic laser acceleration and high trapping efficiency
  - Observed >20% energy gain
  - Observed up to 80% trapping efficiency
  - Observed energy width of accelerated electrons as low as 0.36% ($1\sigma$)
  - Demonstrated ability to control microbunch phase using chicane
  - Model agrees well with data
- STELLA success brings us closer to someday realizing a practical laser linac

# LWFA Staging – Definition?

SLAC

Proceedings, Conference Light at extreme intensities 2011

## Electron Acceleration in a Two-Stage Laser Wakefield Accelerator

Ruxin Li[a], Jiansheng Liu[a], Changquan Xia[a], Wentao Wang[a], Haiyang Lu[a], Cheng Wang[a], Aihua Deng[a], Wentao Li[a], Hui Zhang[a], Xiaoyan Liang[a], Yuxin Leng[a], Xiaoming Lu[a], Cheng Wang[a], Jianzhou Wang[a], Baifei Shen[a], Kazuhisa Nakajima[a,b,c], and Zhizhan Xu[a]

[a] *State Key Laboratory for High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences (CAS), Shanghai 201800, P.R. China.*
[b] *High Energy Accelerator Research Organization 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan*
[c] *Shanghai Jiao Tong University, Shanghai 200240, P. R. China*

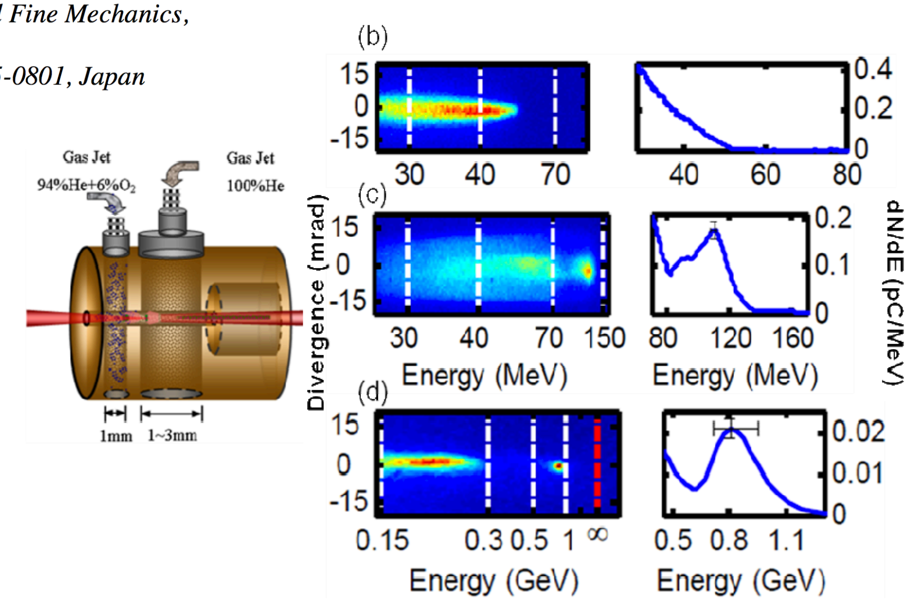



**FIGURE 2.** Results of two-stage accelerator experiment. (a) Schematic of two-stage LWFA. (b)-(e) Single-shot e-beam energy spectra and their lineouts (b) from the injector cell driven by 60 TW focused at a 1.2 mm distance, (c) from the 1-mm accelerator cell for the drive power 60 TW, and (d) from the 3-mm accelerator cell for the drive power 45 TW.

# LBNL Staging – S. Steinke AAC2016

SLAC

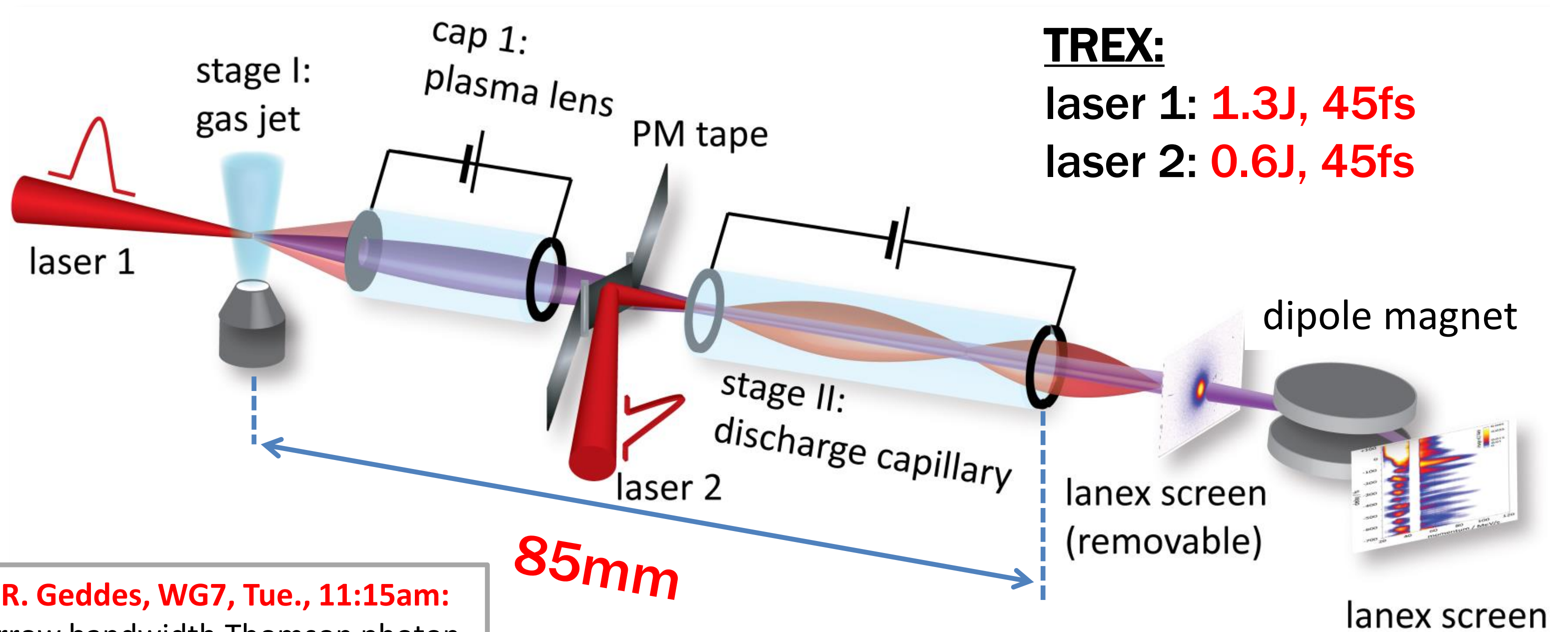
## Multistage Coupling of two independent LPAs

**Stage I:** gas jet - injector

**Coupling II:** tape-driven plasma mirror

**Coupling I:** active plasma lens

**Stage II:** discharge capillary- accelerator

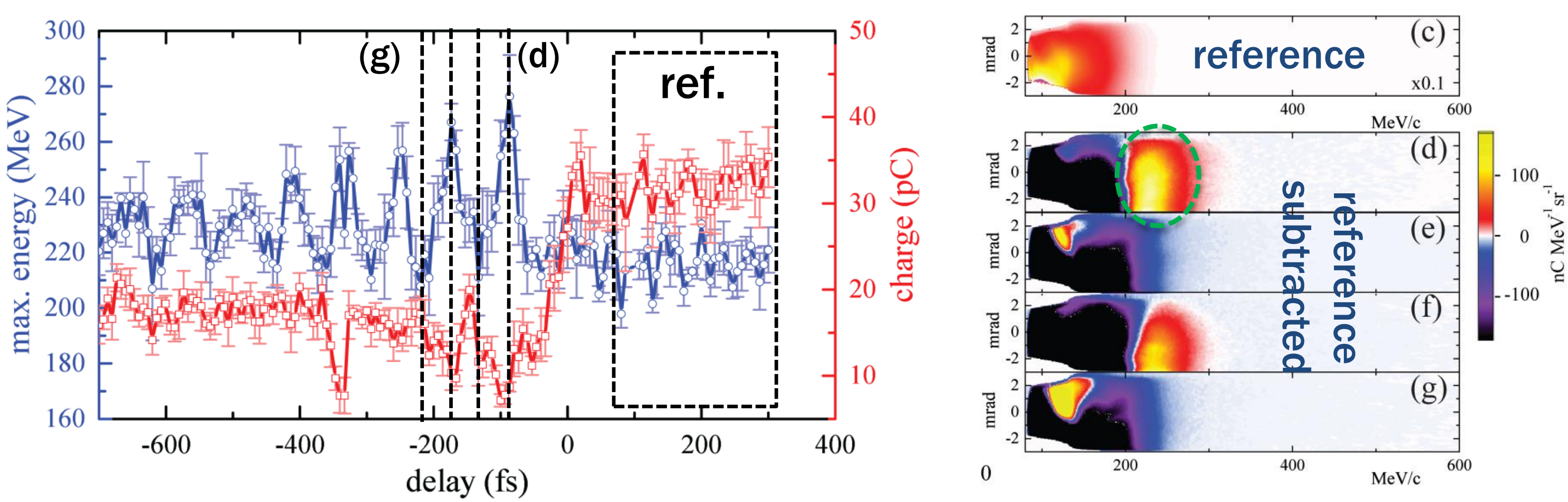



**C.G.R. Geddes, WG7, Tue., 11:15am:**
"Narrow bandwidth Thomson photon source development using LPAs"

# LBNL Staging – S. Steinke AAC2016

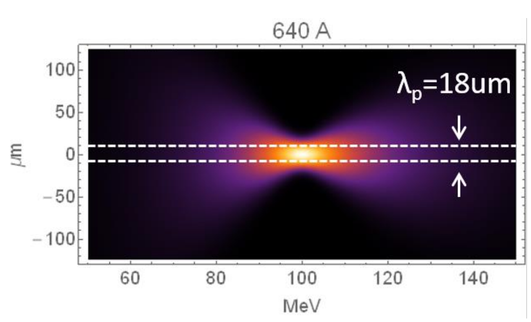
## Staging Experiment: Energy gain of witness beam by timing of second laser (wake phase)

Modulation period of 80fs consistent with a plasma frequency at a density of $2\times10^{18}cm^{-3}$




S. Steinke et al., Nature **530**, 190 (2016)

Previous plasma lens calculation suggest that 1.2pC of trapped charge corresponds to a wake trapping efficiency of 30%, **but it's not that easy** (unfortunately)

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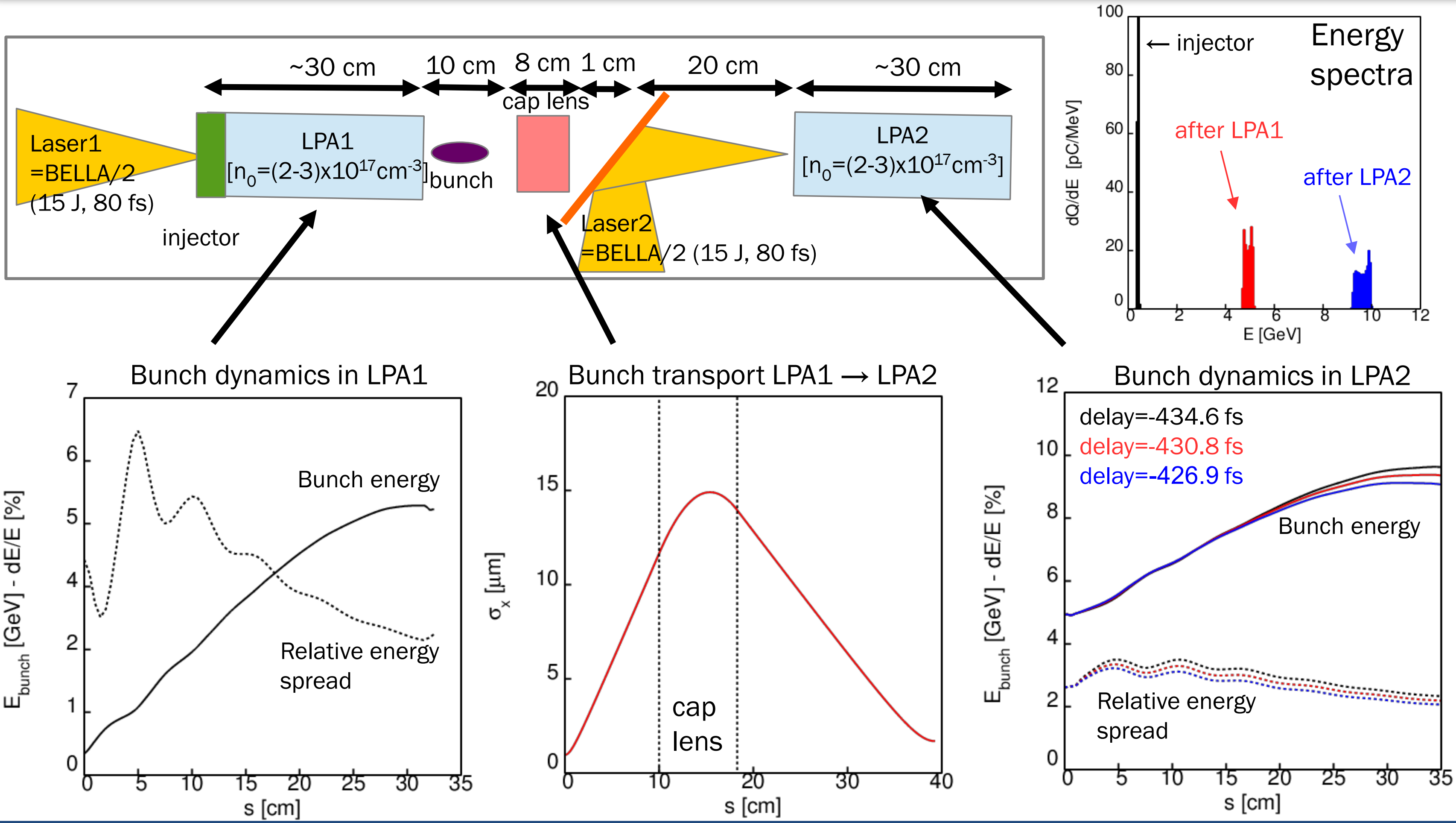
# LBNL Staging – S. Steinke AAC2016

SLAC

## ~10 GeV electron beams from STAGING experiment using BELLA: simulations show high efficiency capturing and acceleration in LPA2 of the bunch produced by LPA1



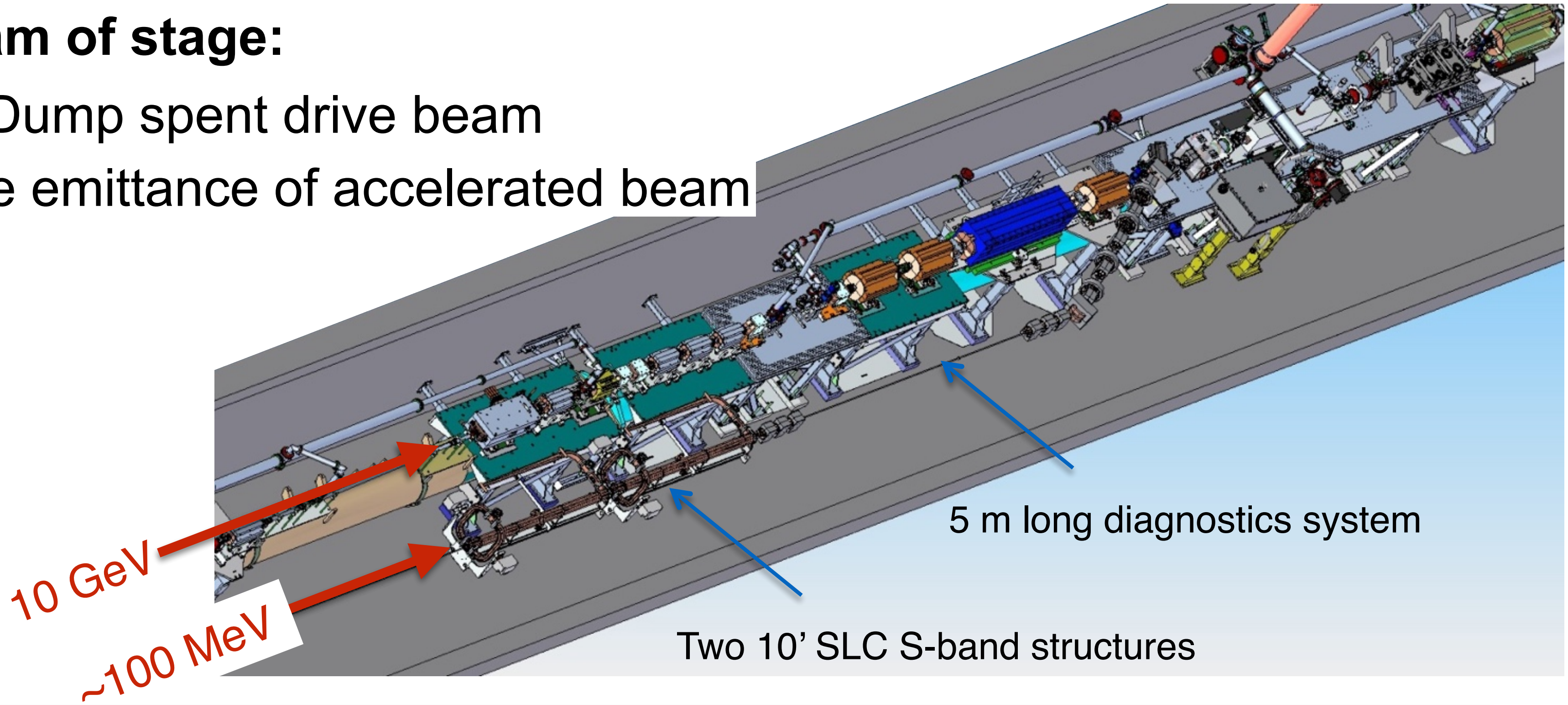
# Staging Will Be Required to Reach Very High Energies

**Upstream of stage:**

- Inject high-brightness witness bunch from independent source
- Tailored current profiles for maximum efficiency
- Investigate tolerances on timing, alignment

**Downstream of stage:**

- Extract/Dump spent drive beam
- Preserve emittance of accelerated beam

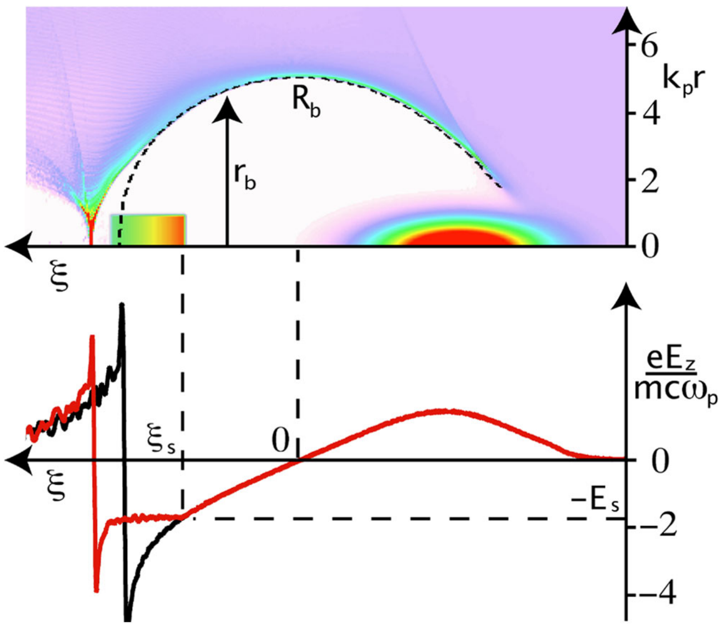


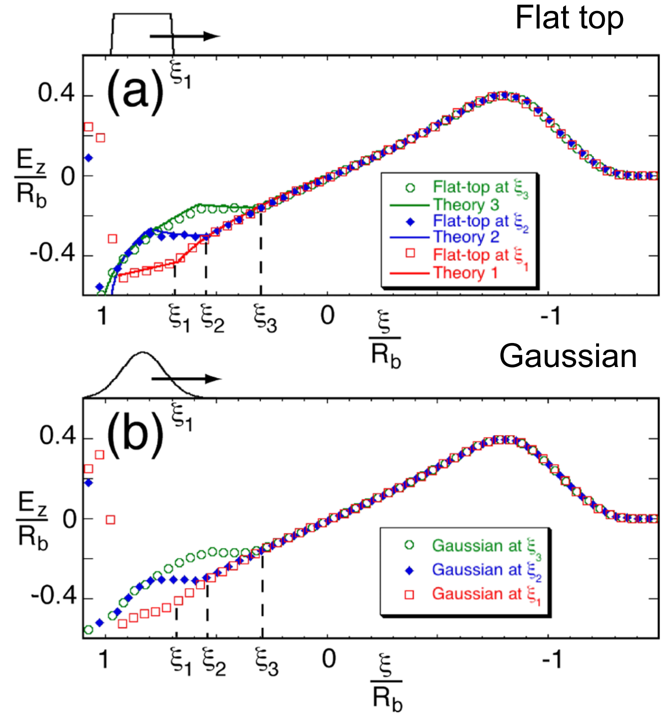

FACET-II will have the tools to study issues relevant to staging multiple plasma cells together as desired for very high energy applications

# Beam Loading in Non-linear Wakes

SLAC

## Theoretical framework, augmented by simulations, provides a recipe



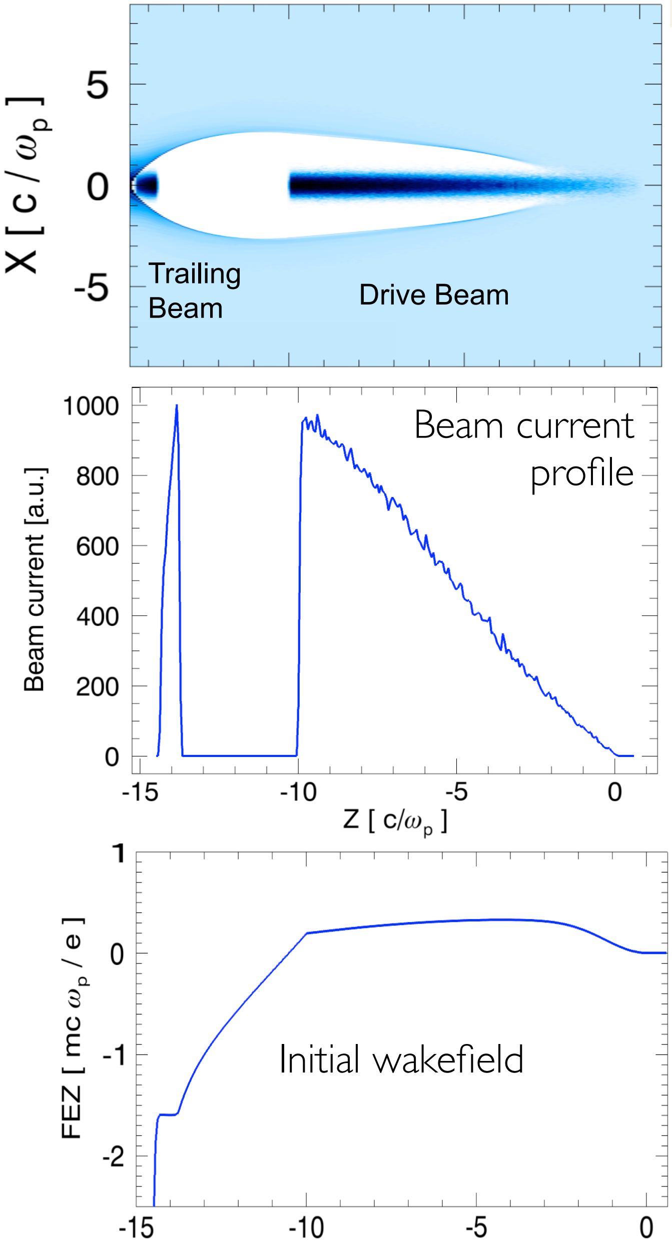




Roadmap emphasizes the need to answer the question: Is it possible to strongly load the longitudinal wake without strong transverse wakes and BBU?

- Relativistic Beams provide a non-evolving wake
- Possible to nearly flatten accelerating wake – even with Gaussian beams
- Gaussian beams provide a path towards $\Delta E/E \sim 10^{-2} - 10^{-3}$
- Applications requiring narrower energy spread, higher efficiency or larger transformer ratio ➡ Shaped Bunches

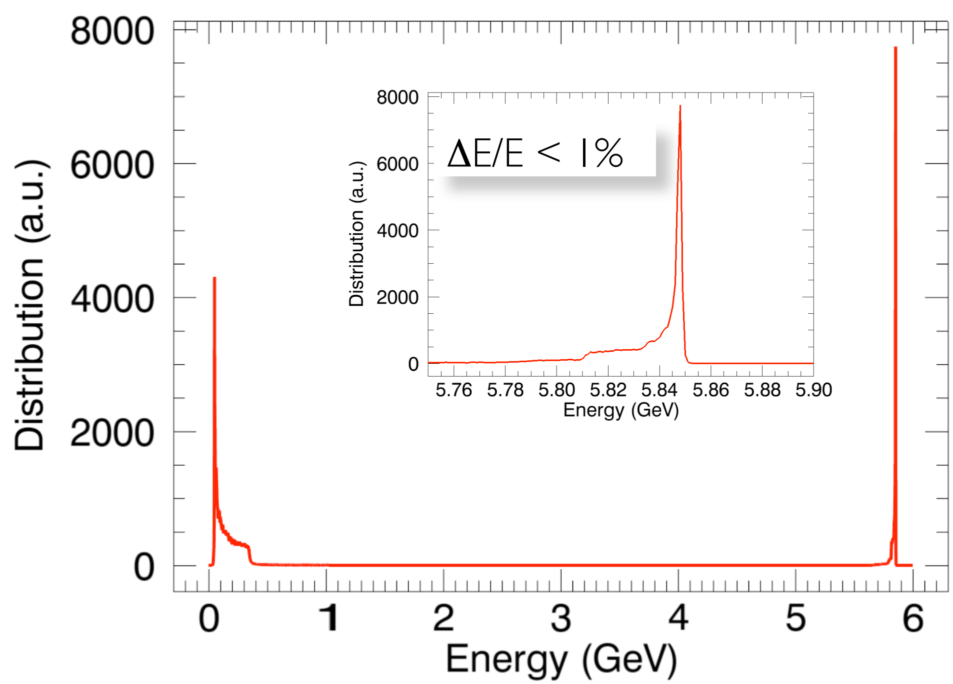
$$\mathcal{L} = \frac{P_b}{E_b}\left(\frac{N}{4\pi\sigma_x\sigma_y}\right)$$

# Higher Transformer Ratios – Lower Drive Beam Energy, Fewer Stages and Higher Efficiency




Shaped bunches have many benefits:

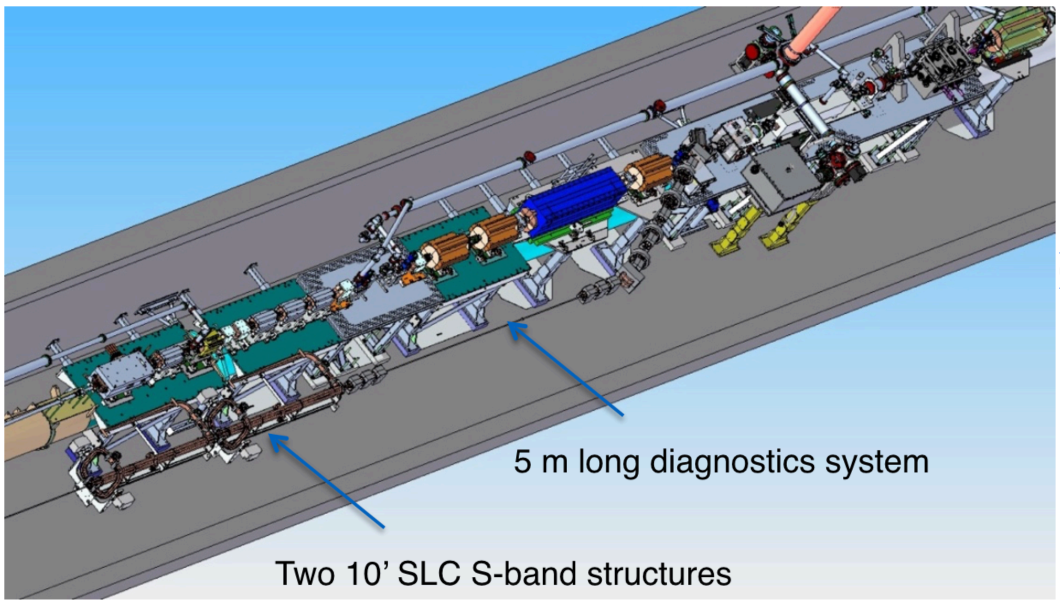
- Reduced energy spread
- Maximizes energy boost from a single stage
- Different source & emittance for drive/witness

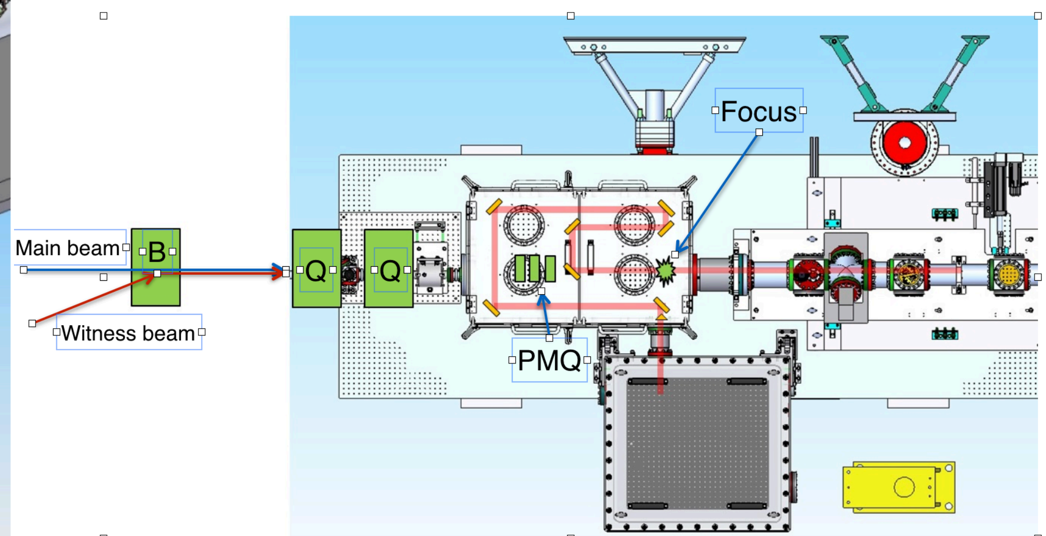



**Need to investigate maximum transformer ratio that still preserves beam quality**

# Witness Bunch Injector Tunnel Installation

- Gun and injector RF placed near last BC3 bend
- Horizontal dog-leg to compress bunch to <10 um
- Final quad triplet are small permanent magnets (PMQ)
- Quadrupoles focus < 10 um
- Preliminary design: 100MeV, 3kA – needs refinement and user feedback




Witness bunch injector concept, a possible solution for staging studies and high transformer ratio experiments, is compatible with FACET-II design

*Talks by Me, Vladimir Litvinenko, Joe Frisch, Wei Lu*

# FACET Witness Bunch Injector Optics Design

Glen White, SLAC

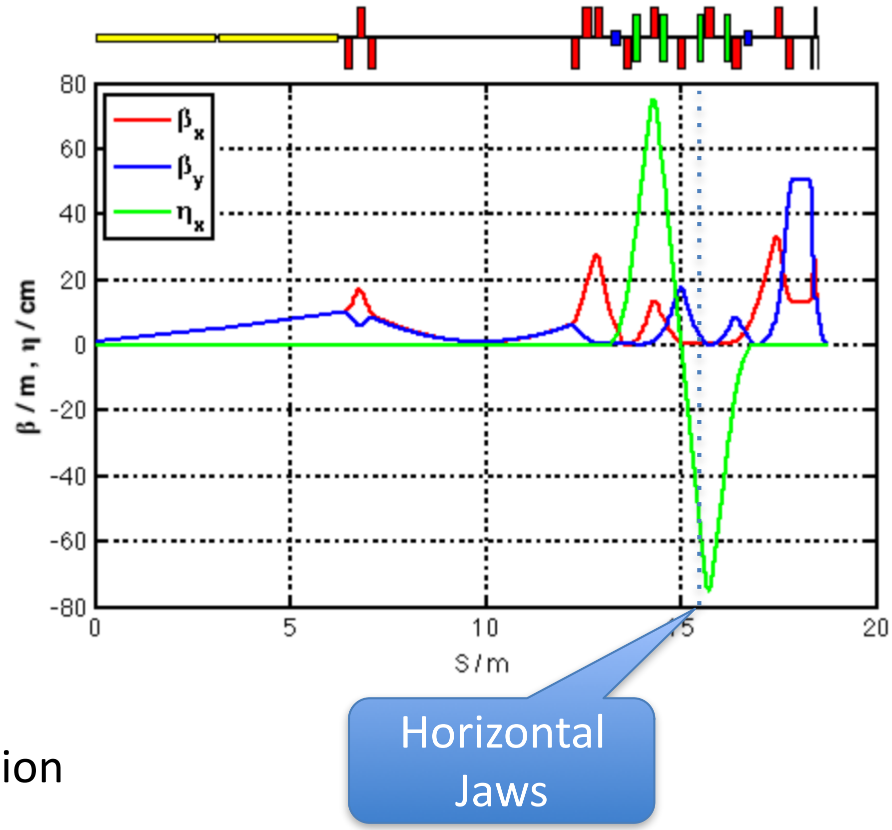
July 25, 2014

# Overview

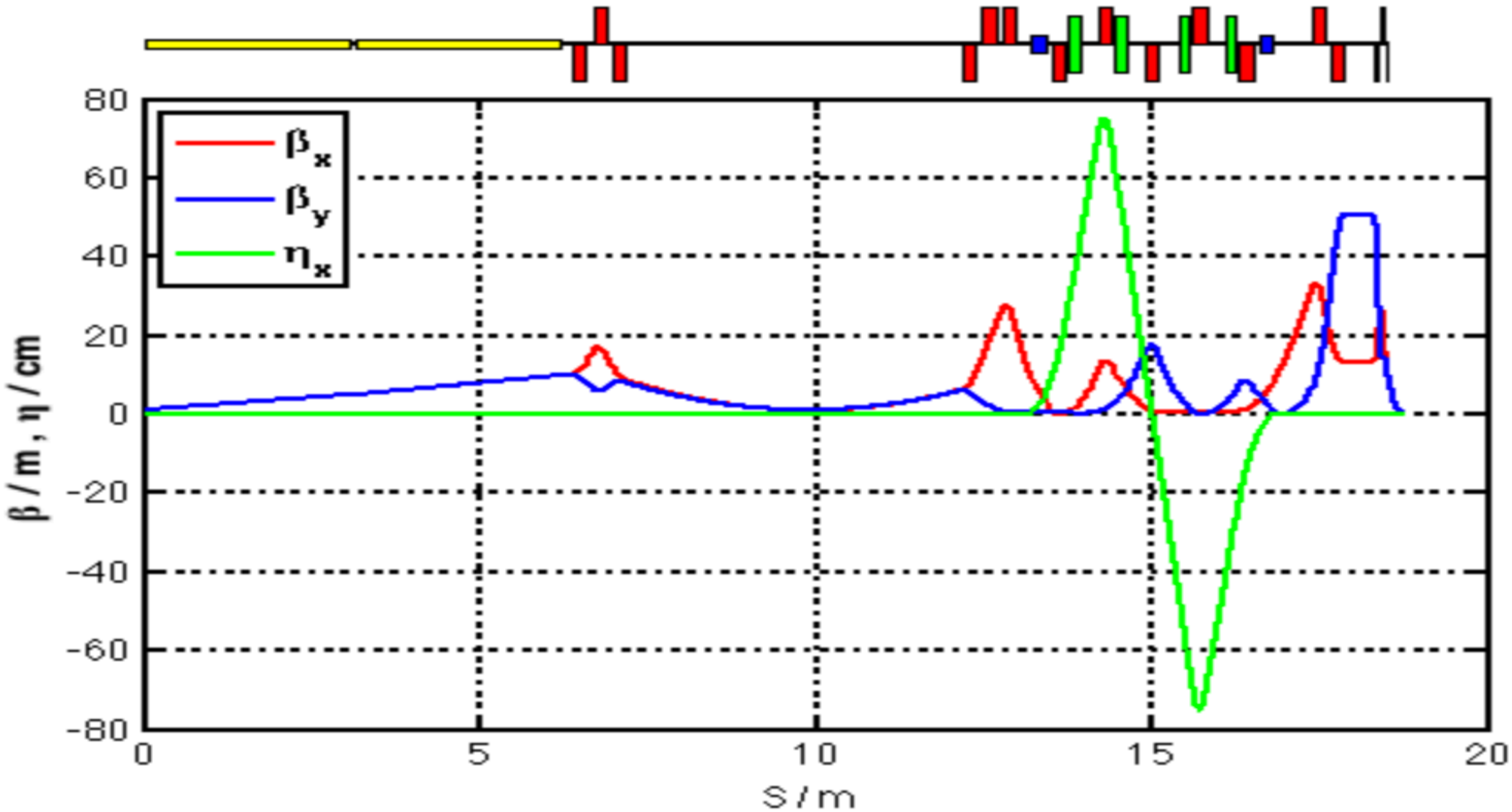
- Independent witness bunch injector for S20
  - Dogleg optics with injection co-linear with main 20 GeV beam + focusing into E200 plasma volume. Delivered beam parameters:
  - E=100 MeV
  - $\sigma_x/\sigma_y/\sigma_z < 10$um, peak current > 1kA
- Source parameters:
  - Q = 350 pC
  - $\gamma\varepsilon_{x,y}$ = 1um.rad
  - Bunch length = 1ps FWHM, 300A peak current.

# Acceleration, Matching Section and Dogleg

- 2 x 3m SLAC s-band LCAV structures
  - 57.3 MV / structure (18.7 MV/m)
  - Phase = 30.24 deg. off-crest
    - Provides chirp for bunch compression
- Matching by 2 quad triplets
  - Waist in 5m drift section for beam profile diagnostics
  - Provide required match parameters -> dogleg
- Dogleg for injection into main beam line and provide bunch compression
  - Bend angle = 450 mrad (25.78 deg), R56 = 13.6 mm
  - Provide Jaw location with large η/β ratio for reduction of dispersive beam tails at IP
  - Provide sextupoles for correction of chromaticity & second-order dispersion at the final focus location.



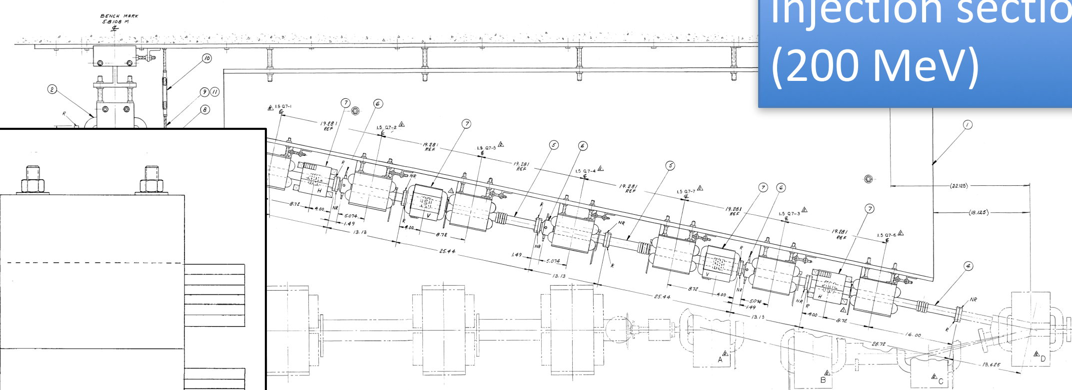
# Final Focus

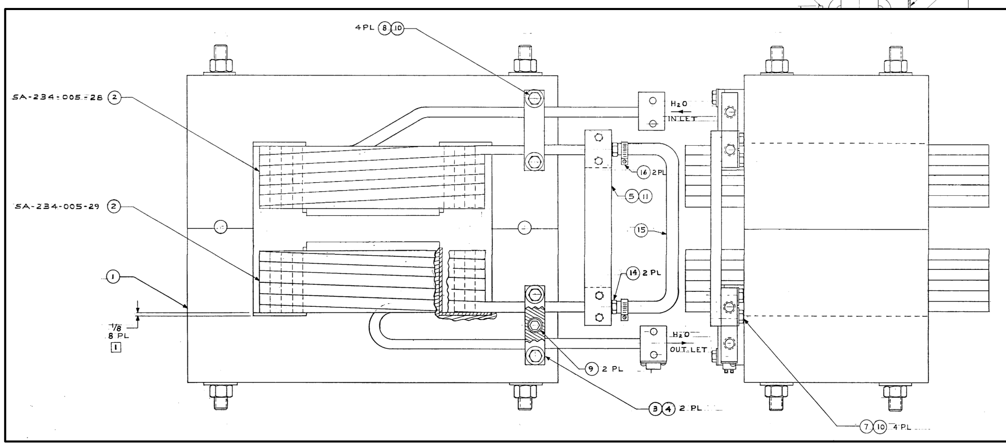



- Second bend of dogleg common with drive beam
- Focusing provided by final electromagnet doublet and PM quad triplet
  @IP: $\beta_{x,}\beta_y$ = 5mm @ PENT => $\sigma_{x,}\sigma_y$ = 5um for $\gamma\varepsilon_{x,y}$ = 1um.rad
  - L* = 25 cm (d/s face of final Quad -> PENT)
- Need to pre-compensate for bending of drive beam and re-match drive beam FFS for (relatively weak) final focus quads.
  - Also pre-compensate for added drive beam horizontal dispersion.

# Magnets

S1 Linac positron re-injection section (200 MeV)



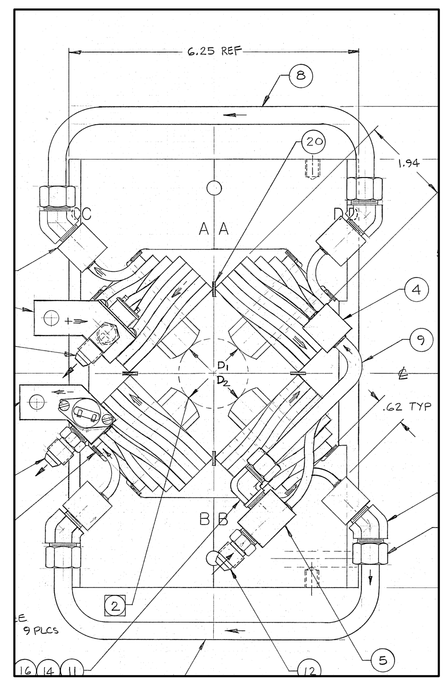



"5D7.1"

- L = 0.2032 m
- 12 deg @ 200 MeV
- HGAP = 0.0133 m
- Core Width = 0.2286 m
- Width = 0.3556 m
- Height = 0.292 m
- BDES = 1.5 kG.m @ 290A

"1.57Q7"

- L = 0.197m
- Aper = 0.0192 m
- Width = 0.1588 m
- Height = 0.292 m
- BDES = 31 kG @ 90A



# Magnet List

| Name | Type | BDES |
|---|---|---|
| QM1 | 1.57Q7 | -3.5 kG |
| QM2 | 1.57Q7 | 6.645 kG |
| QM3 | 1.57Q7 | -3.5 kG |
| QM4 | 1.57Q7 | -5.92868 kG |
| QM5 | 1.57Q7 | 1.19209 kG |
| QM6 | 1.57Q7 | 7.35059 kG |
| QDL1 | 1.57Q7 | -11.402 kG |
| QDL2 | 1.57Q7 | 9.67 kG |
| QDL3 | 1.57Q7 | -9.0 kG |
| QDL4 | 1.57Q7 | 9.67 kG |
| QDL5 | 1.57Q7 | -11.402 kG |
| SDL1 | ??? | 650.0 $kG.m^{-1}$ |
| SDL2 | ??? | 80.0 $kG.m^{-1}$ |
| SDL3 | ??? | 80.0 $kG.m^{-1}$ |
| SDL4 | ??? | 650.0 $kG.m^{-1}$ |
| BDL1 | 5D7.1 | 1.5 kG.m |
| BDL2 | 5D7.1 | -1.5 kG.m |
| QFF1 | 1.57Q7 | 7.66465 kG |
| QFF2 | 1.57Q7 | -6.87686 kG |

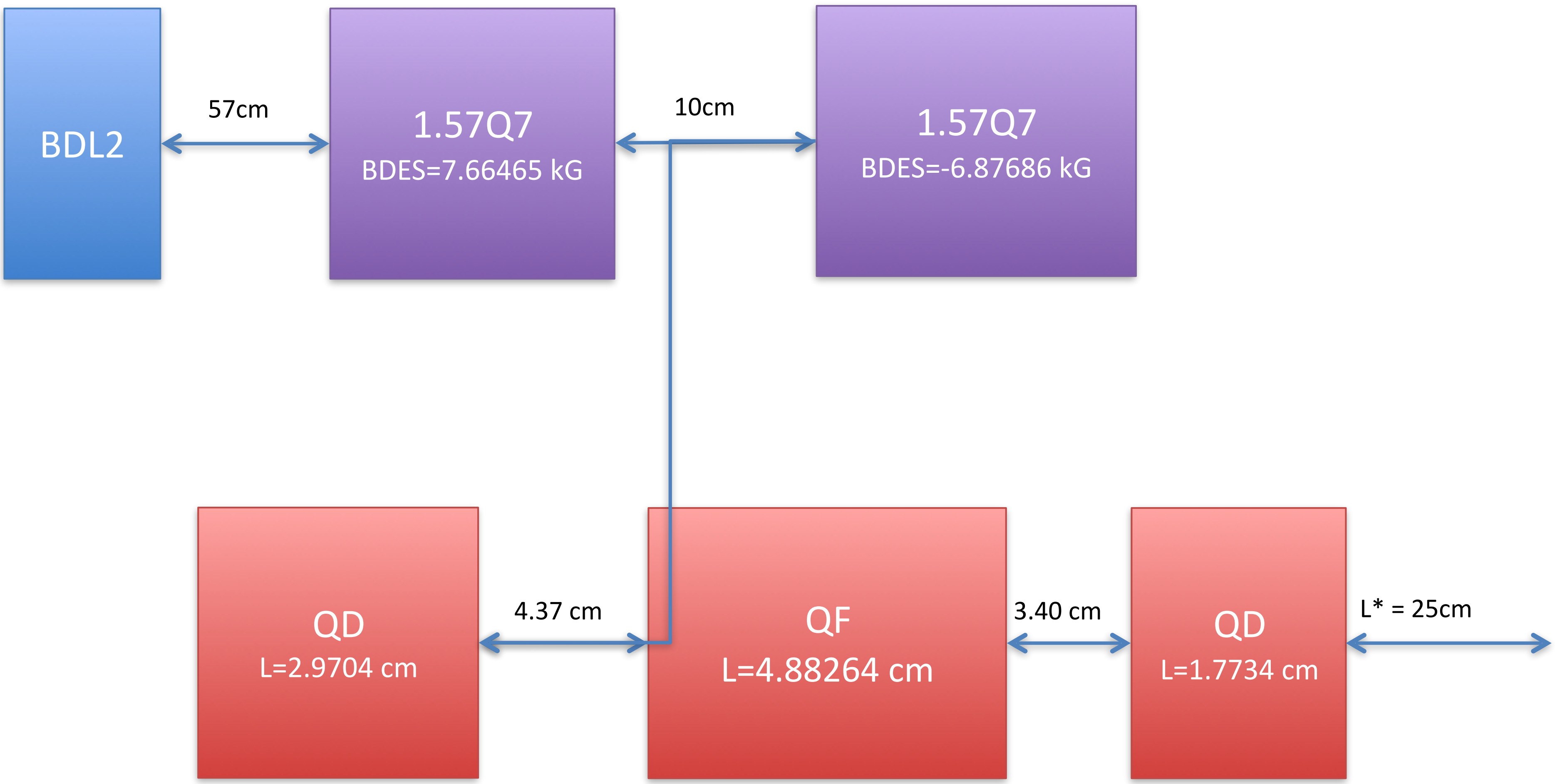
Magnet Count

- Quads = 13
- PM triplet = 1
- Sextupoles = 4
- Bends = 2
- Correctors = ?

Sextupoles

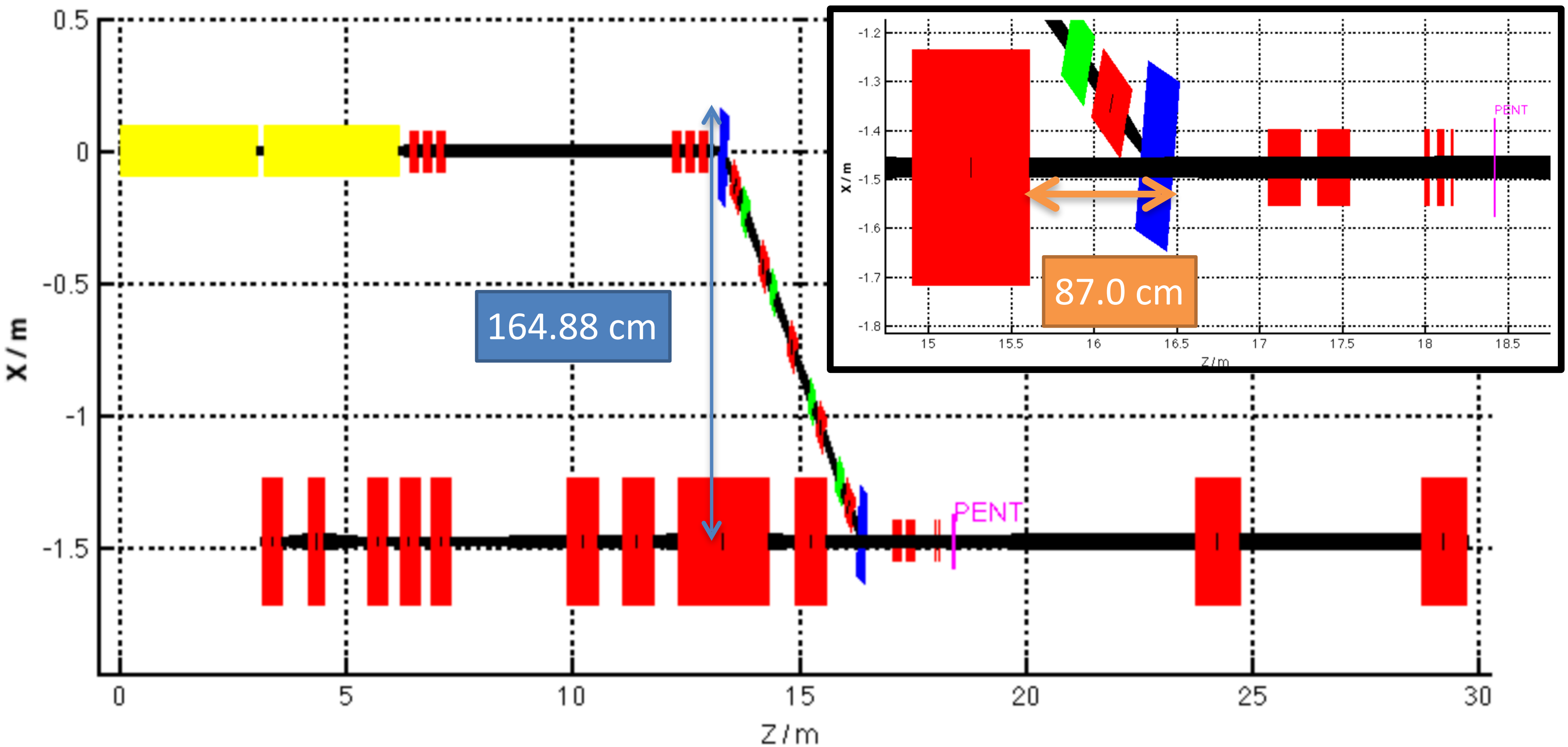
- Assume same geometry as 1.57Q7

# FFS Quad Parameters




- PM triplet quads = 663 kG/m

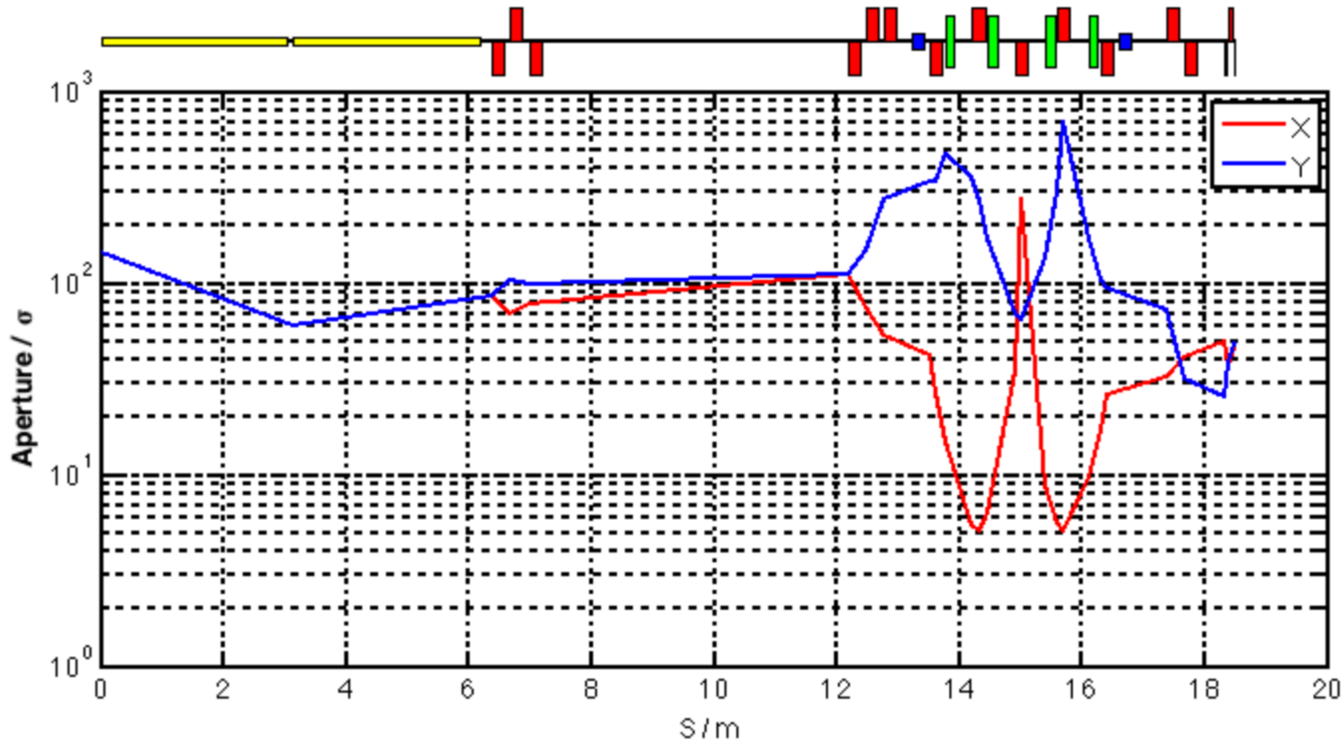
# Integration Into S20 Main Beamline



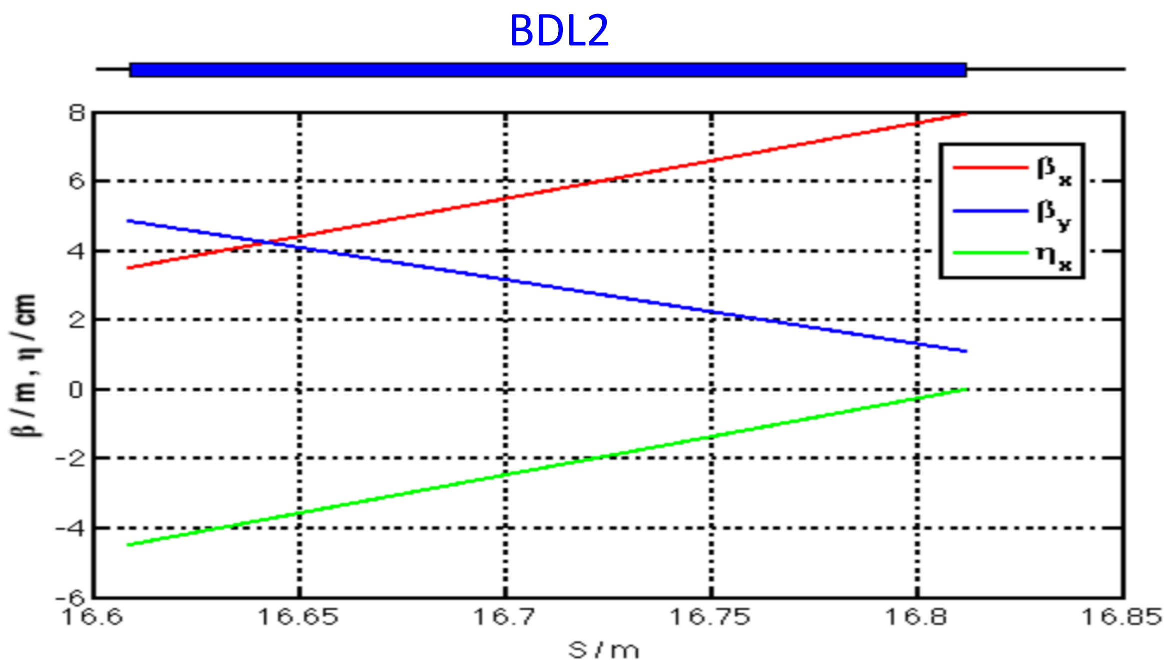

- Scale X-Z plan view showing injector components overlaid on S20 QFF1 -> QS2 FFS beamline section.
- PENT (plasma chamber entrance shown)
- Black "beam pipe" connects magnet apertures

# Apertures

- Design beam size as function of aperture
  - Aperture defined as half gap between magnet pole tips
- Assume 0.5% dE/E
- 2 locations where max eta_x located may need larger bore magnets here



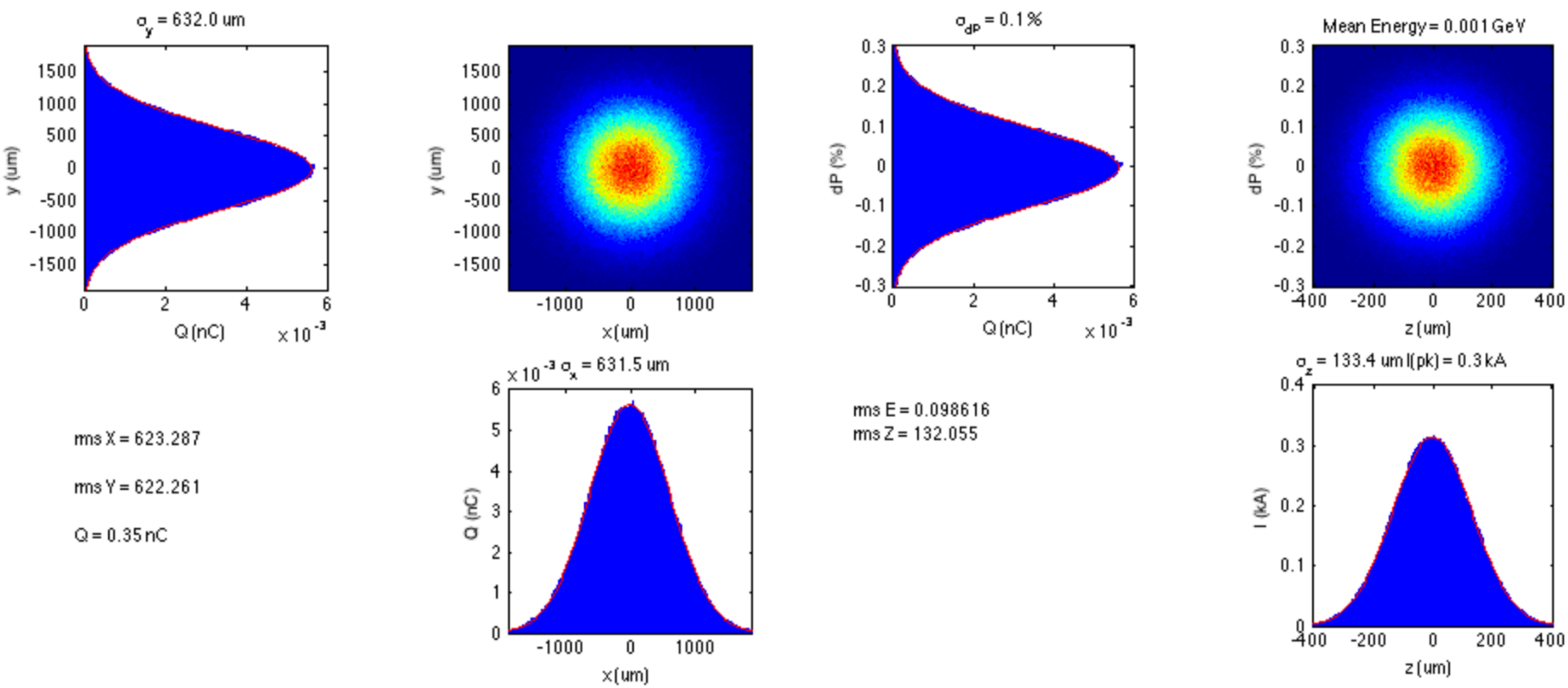
# CSR Considerations



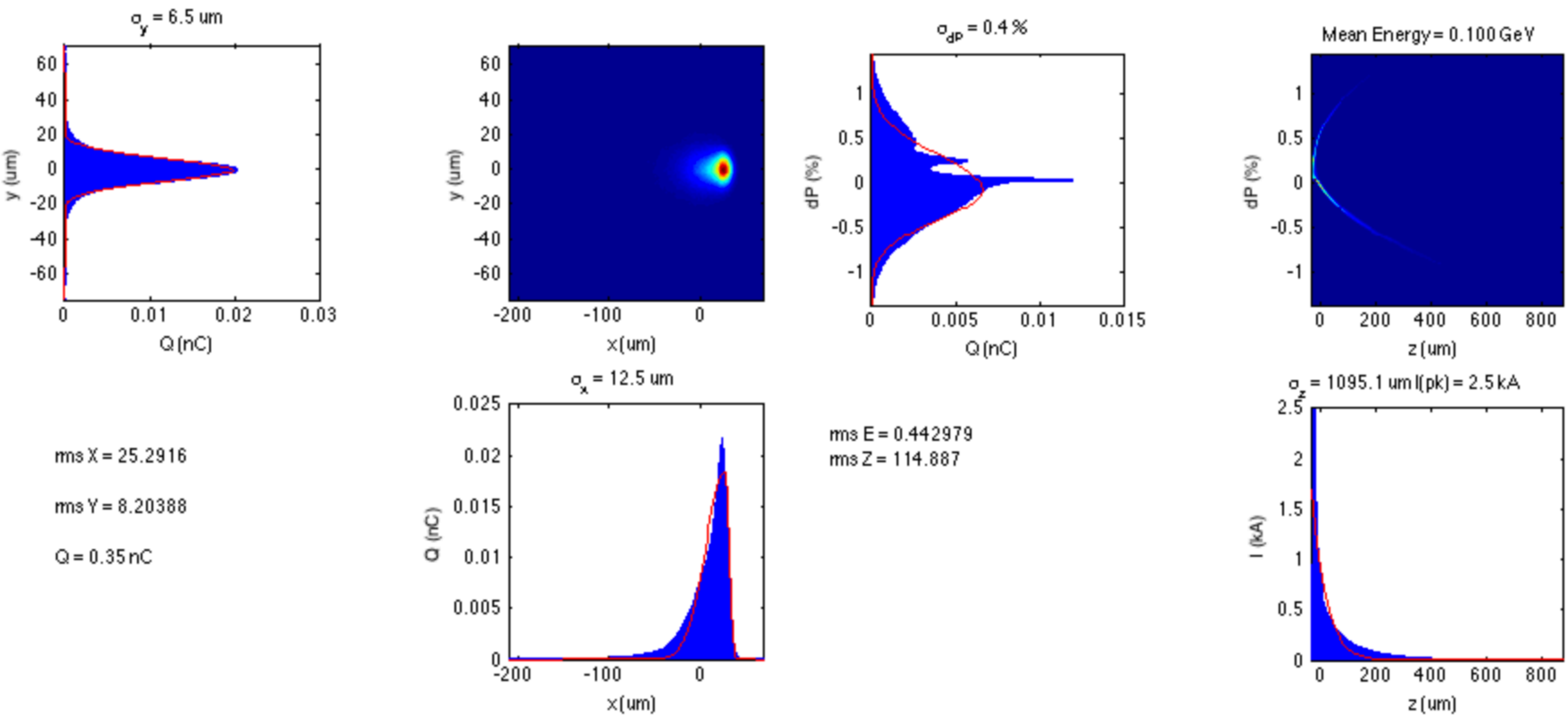

- CSR important in BDL2
- Simulate effects of CSR using Lucretia
  - Uses 1d line-charge model to calculate CSR effects with macro-particle tracking simulation
  - Valid if $\sigma_{x,y} < \rho^{1/3}.\sigma_z^{2/3}$ through bend
    - Use to set beta function requirements in BDL2
    - For 5D7.1 bend and $\varepsilon_{x,y}$ = 1um.rad :
      - Require $\beta_{x,y}$ < **10 m** for $\sigma_z$ = 5um

# Beam Tracking

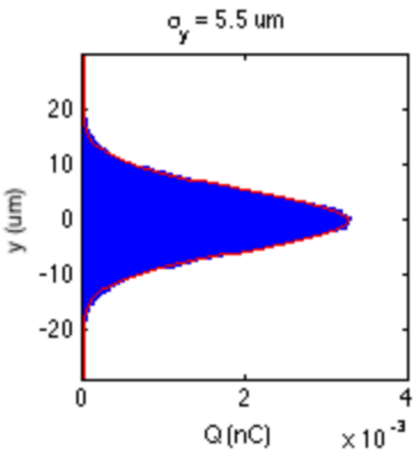
- Lucretia:
  - 1M macro-particles
  - Include CSR in bends and all d/s drifts & magnets
- No transverse space-charge simulation
  - Need to perform e.g. ASTRA simulations to simulate beam distribution entering dogleg for final optimisation of optics.
- Initial beam distribution @ gun:

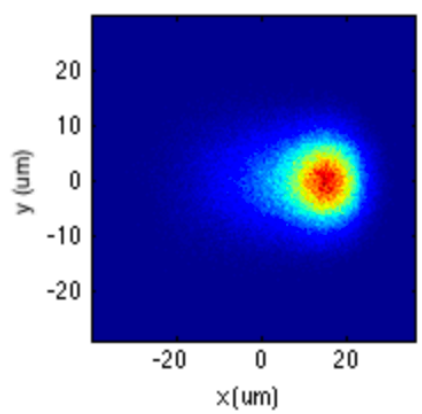


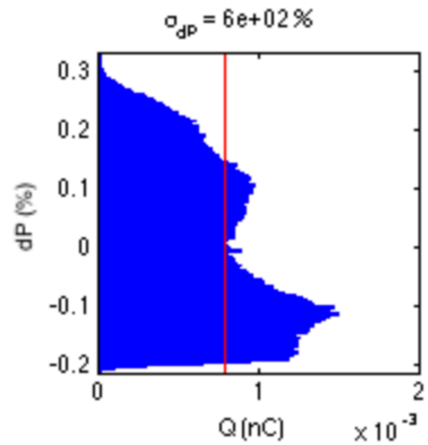
# IP Distribution
## *Jaws OPEN, Sextupoles OFF*

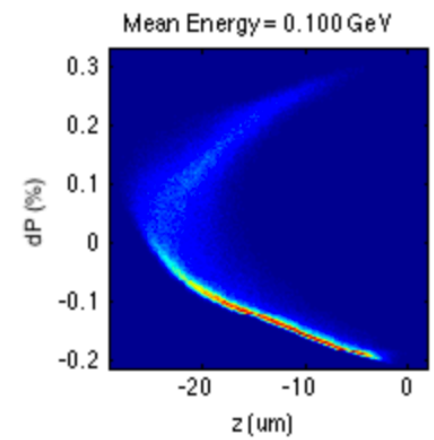


# IP Distribution
# *Jaws 2mm, Sextupoles OFF*



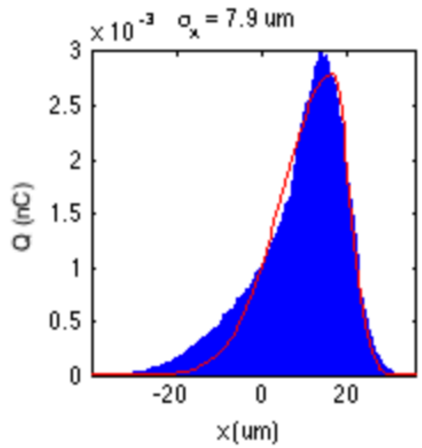



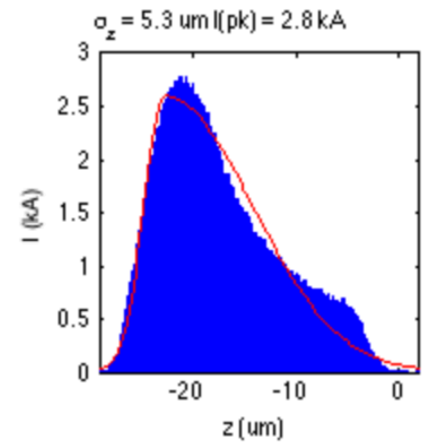

rms X = 10.4715

rms Y = 5.7077

Q = 0.117698 nC

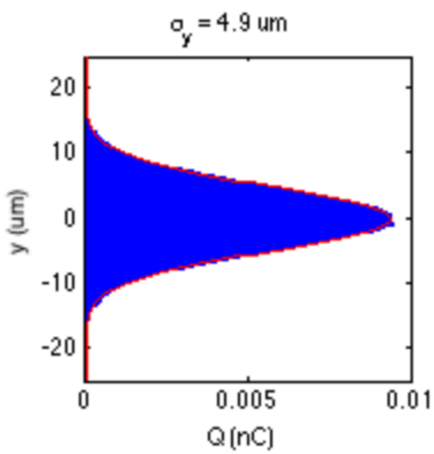


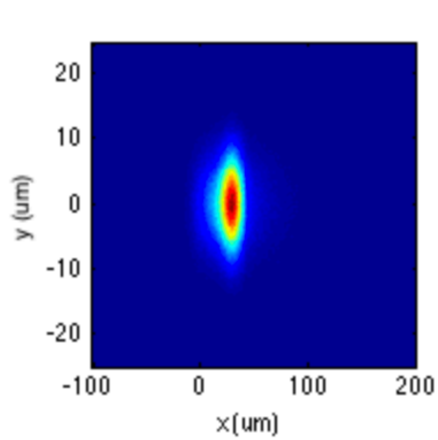

rms E = 0.128783
rms Z = 5.91327

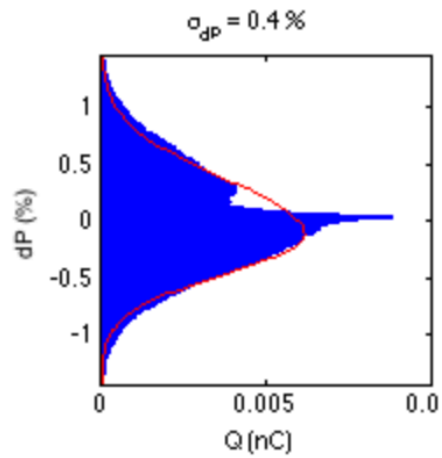


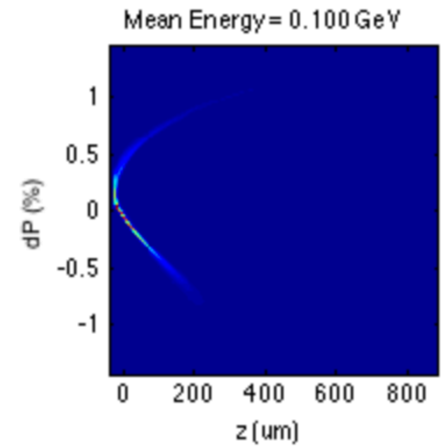
# IP Distribution

## *Jaws OPEN, Sextupoles ON*



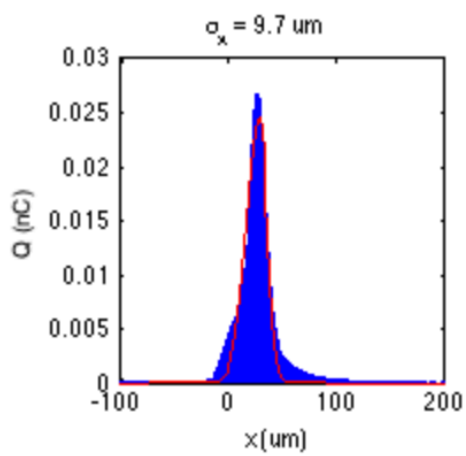



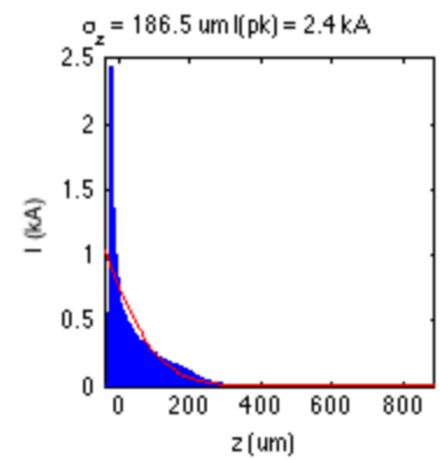

rms X = 19.6163

rms Y = 4.91236

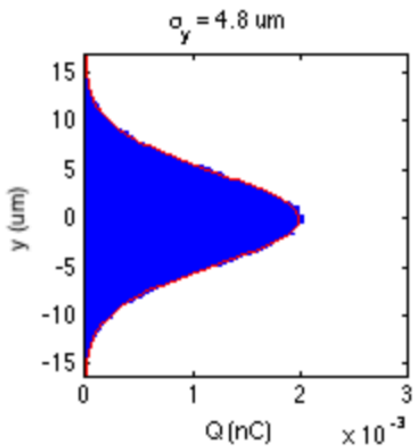
Q = 0.35 nC

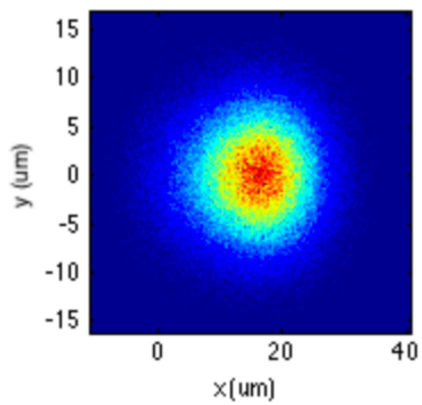


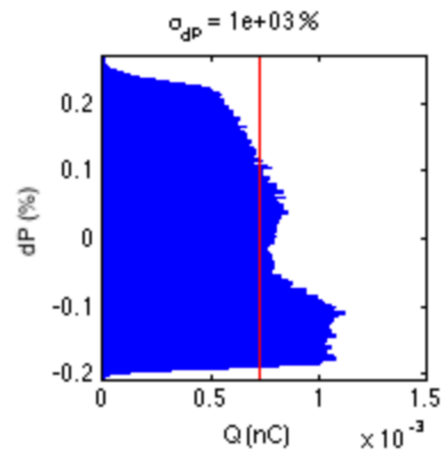

rms E = 0.455039
rms Z = 91.5778

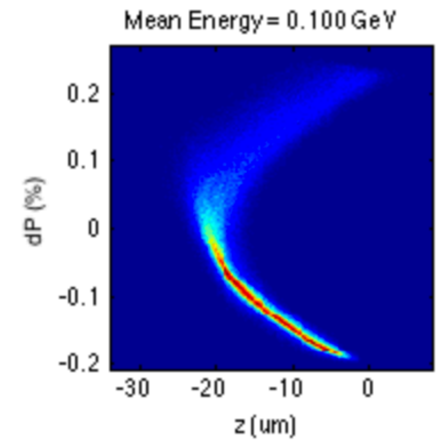


# IP Distribution
## *Jaws 2mm, Sextupoles ON*



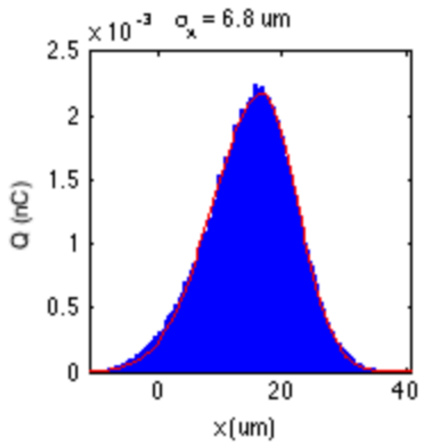



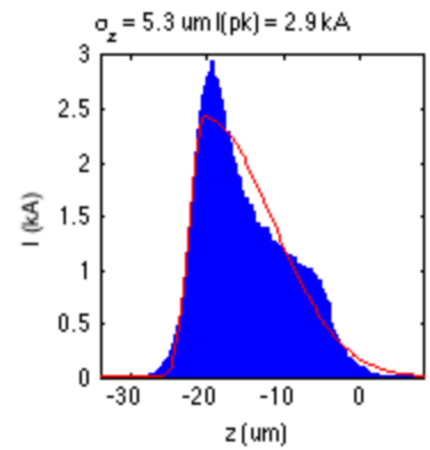

rms X = 7.06359

rms Y = 4.71073

Q = 0.108781 nC

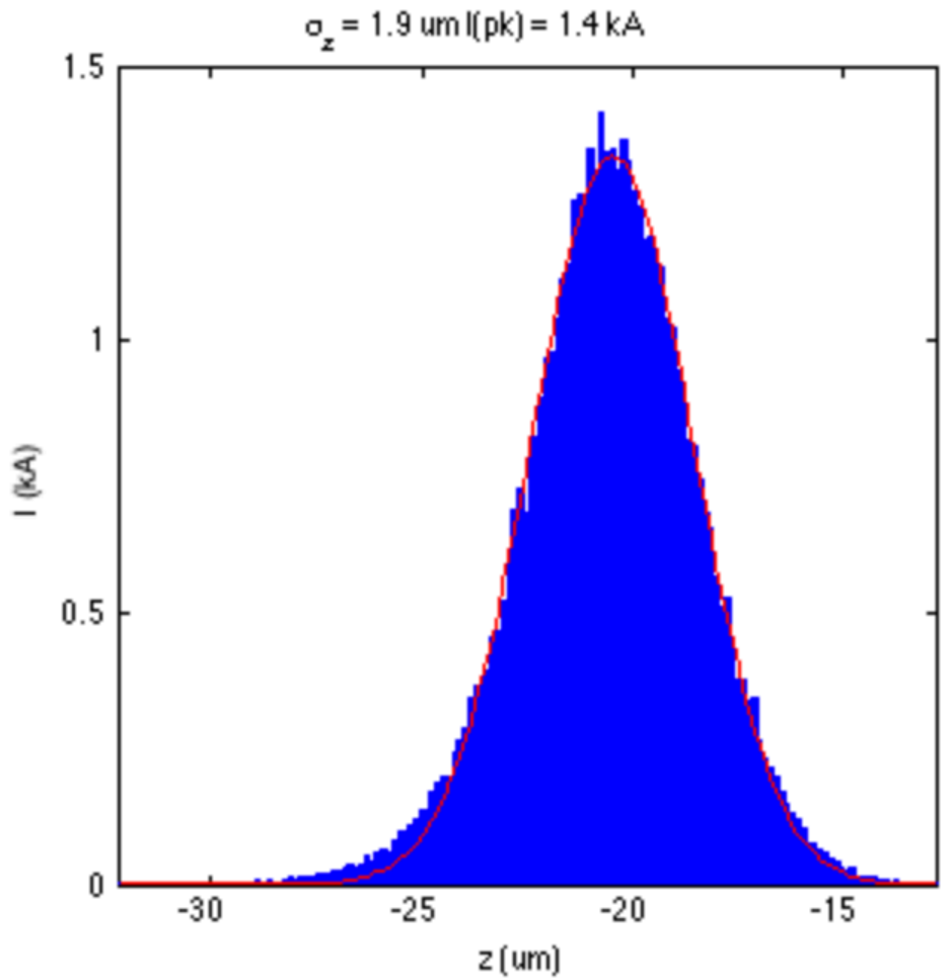



rms E = 0.120954
rms Z = 5.71607



# Contrast

- Bring jaw in to cut core of beam and observe longitudinal contrast.
- Shown is asymmetric gaussian fit to longitudinal profile with tight jaw cuts.



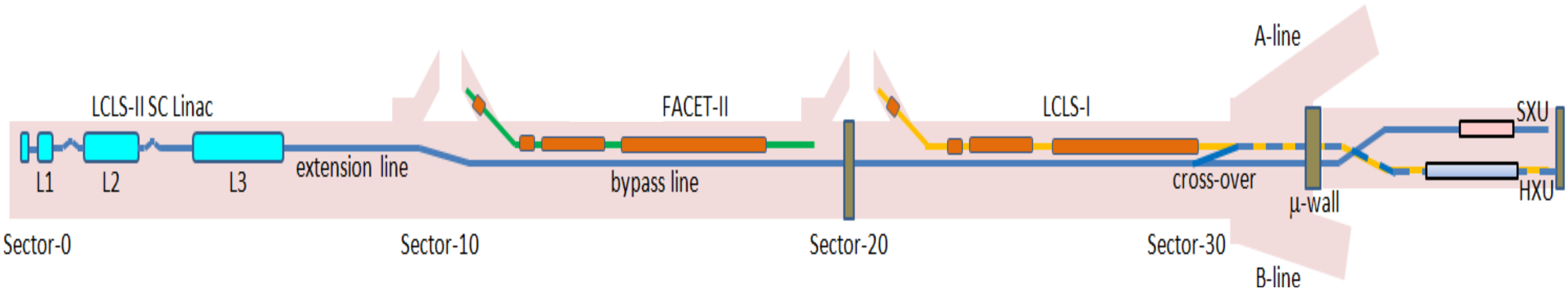
# Summary and Further Work

- Witness bunch injector design for 100 MeV bunch
  7 x 5 um (8x5.5 um NO SEXT) transverse @ 2.9 kA peak current into plasma channel within existing S20 geometry. Need ASTRA simulations to tweak optics design based on realistic beam profiles.
- Identify PROF's / COR's / BPM's for commissioning
- Identify sextupole magnets
- Design main beam orbit and dispersion compensation scheme
- Consider larger bore magnets in peak dispersion locations in dogleg and large beta_y location in FF.
- Check alignment, jitter & field tolerances
- Check optics design and tracking with alternate code
  - e.g. Elegant…
- Design iterations …

# 4 GeV Option

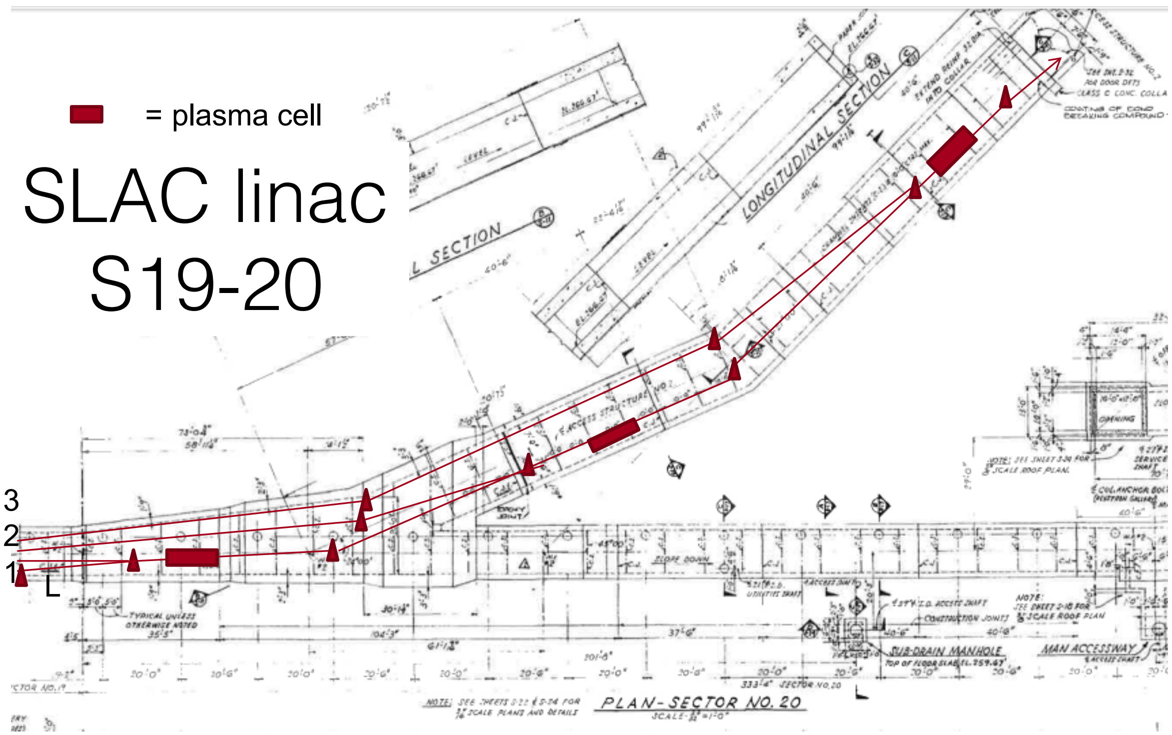
Hypothetically….

- LCLS-II will make more beam than the instruments can handle for some time
- LCLS-II transport will be overhead in S20
- Does it make sense to consider scenarios where we parasitically (symbiotically?) steal pulses and couple into FACET-II beam line?
- Presentation by Joe Frisch after coffee break



# FACET-SX (FACET with staging and hard X-rays) – J. Seeman

**Proposal & Opportunity**: build additional beamlines in the tunnel adit where the scavenger beam is sent to the positron target. Each beamline provides path length difference such that can use existing bunch format to power 2-3 stages for 40+GeV beams. Build new undulator hall using existing shielding blocks on plateau outside of target area and make very hard X-rays for Marie type users.

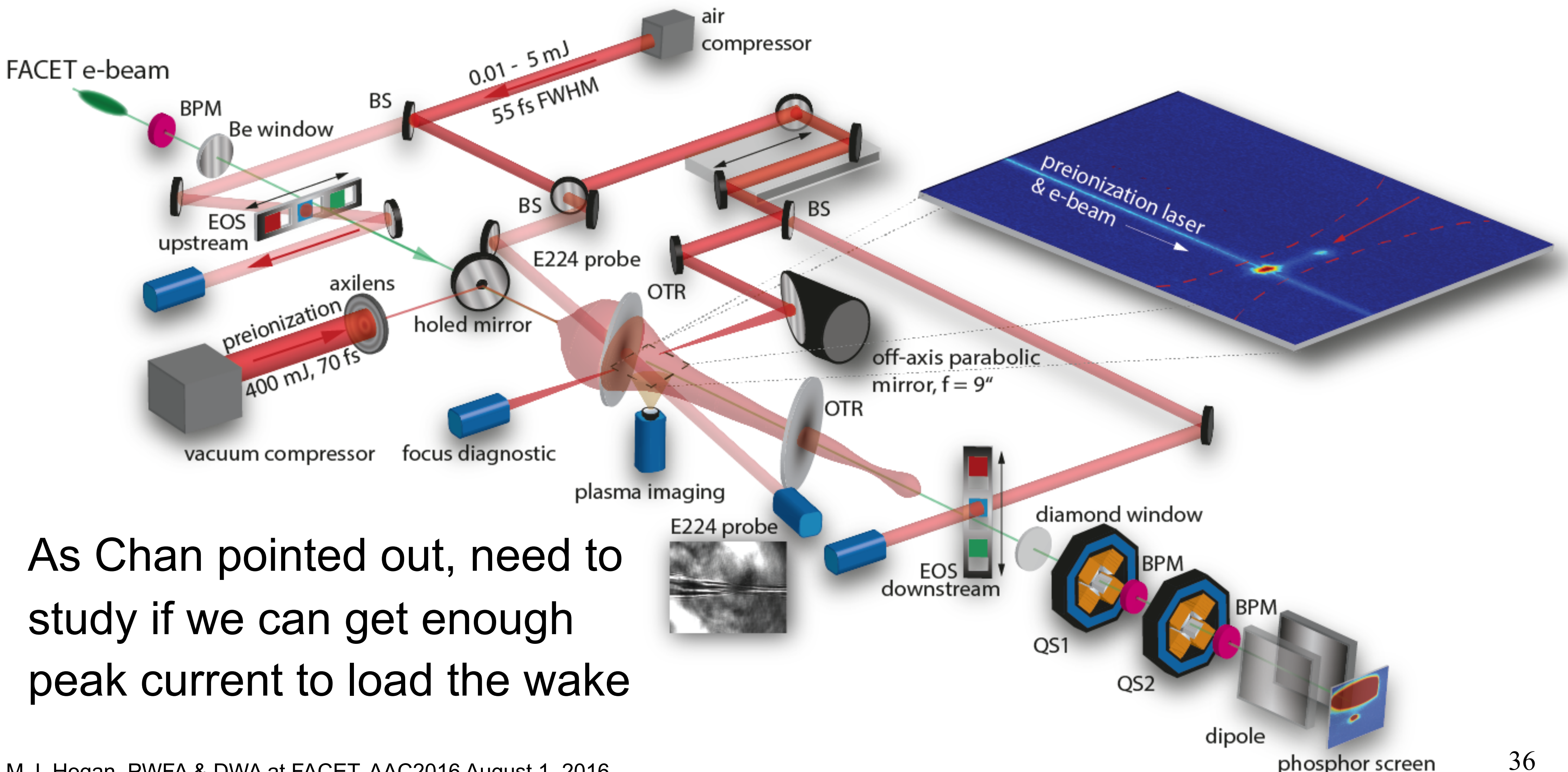




**Challenge**: Cool! and addresses staging and beam quality issues of the roadmap however the large bend angle required to make up the path length for staging will make it difficult (impossible) to preserve the beam emittance between stages.

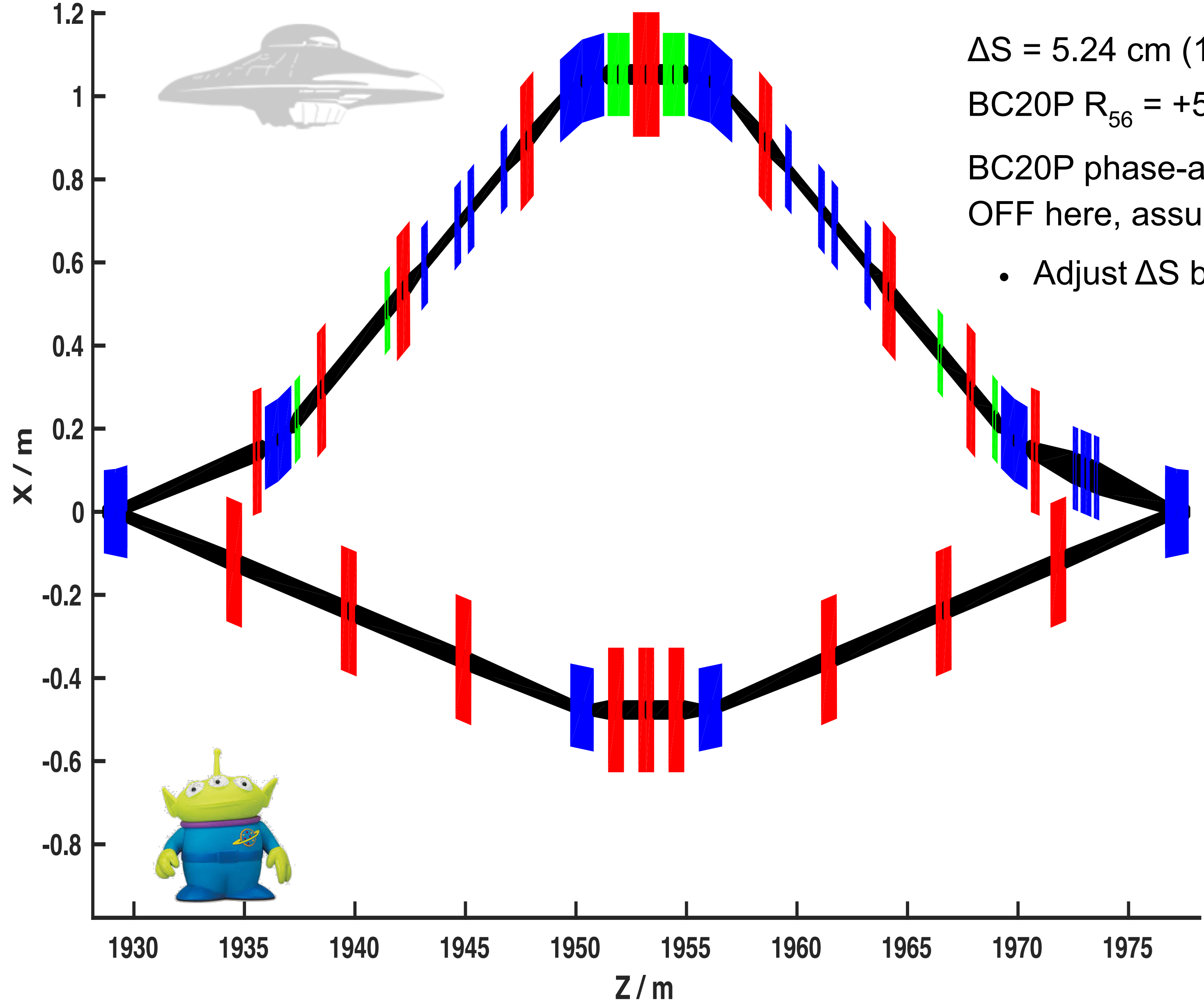
# LWFA Injector

With all this infrastructure + jets and down ramps, it's not much of a stretch to consider low energy LWFA injector – see Wei's talk




As Chan pointed out, need to study if we can get enough peak current to load the wake

# BC20P "Flying Saucer" Chicane – Independent Drive & Witness




ΔS = 5.24 cm (175 ps)

BC20P $R_{56}$ = +5 mm

BC20P phase-adjust chicanes switched OFF here, assumed not used

- Adjust ΔS by changing $E_e$ vs. $E_p$

# Future Linear Collider Requirements

D. Schulte

CERN

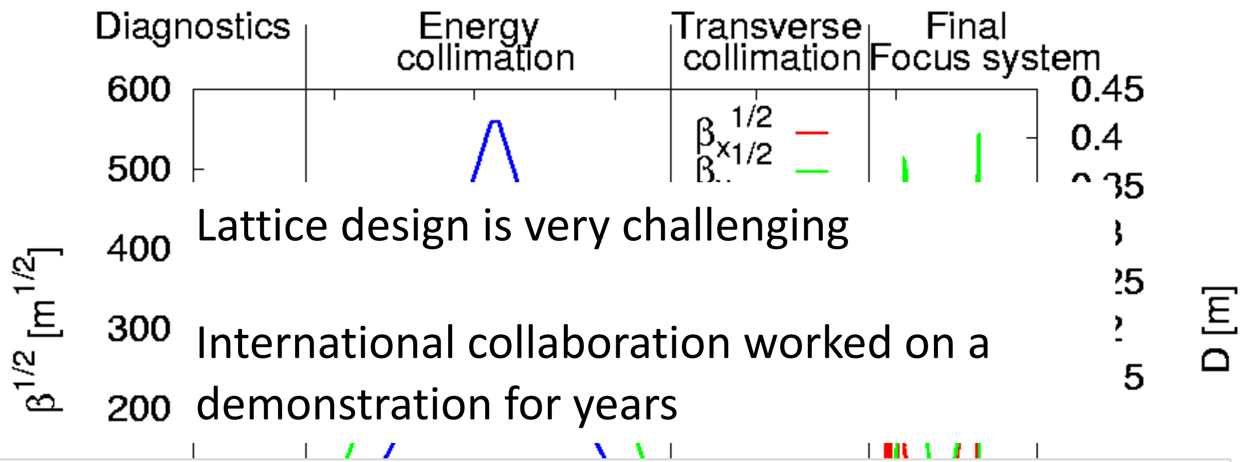
# Energy Spread and Bunch Length

Final focus system has limited energy bandwidth

⇒ Need to limit beam energy spread

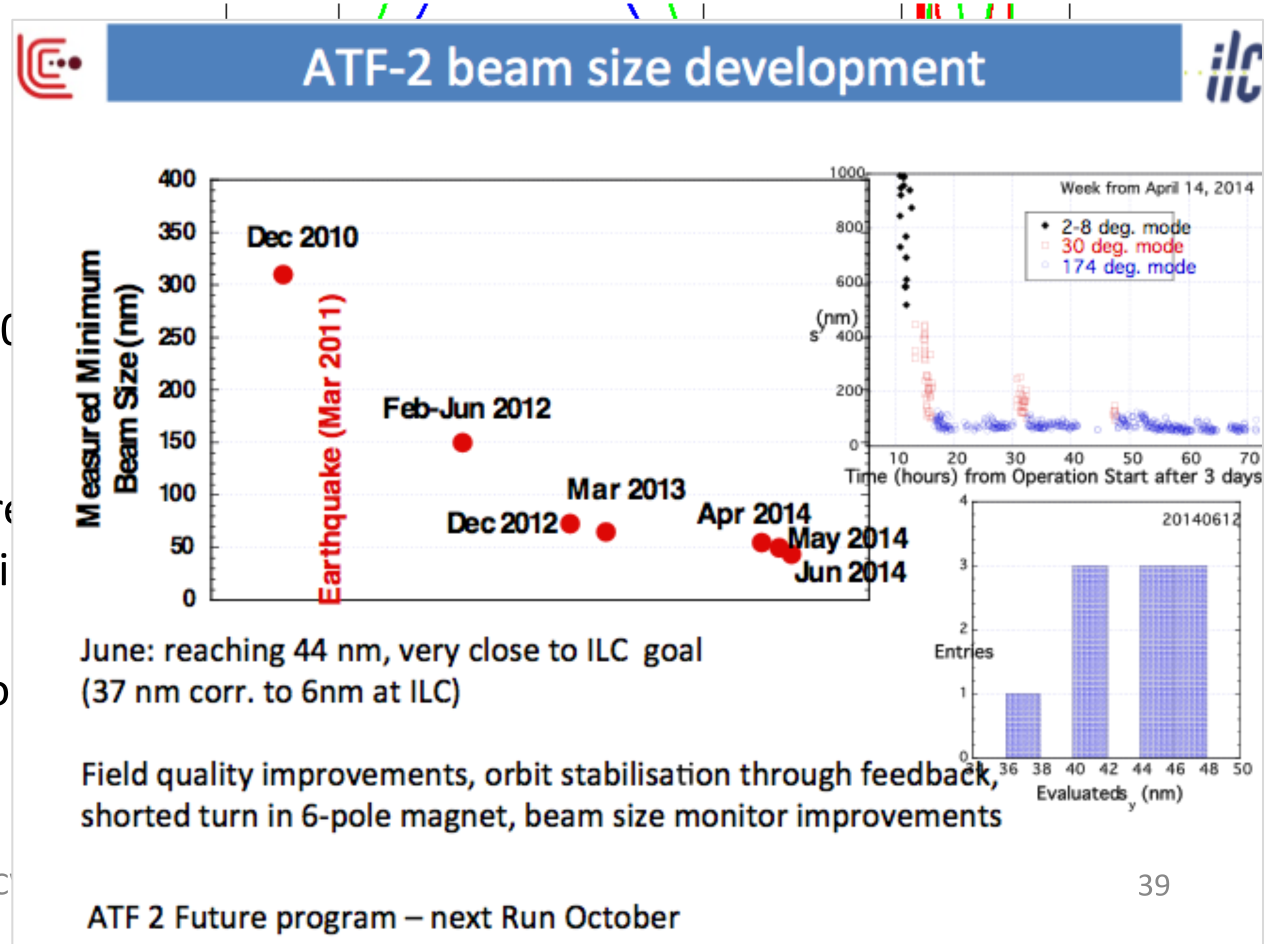
⇒ In CLIC 0.35% RMS spread

⇒ This is an important limitation for CLIC




Lattice design is very challenging

International collaboration worked on a demonstration for years




Energy stability required for CLIC is O((

- Due to limited final focus system acceptance
- Corresponds to 0.2°(=15μm) cohere phase tolerance drive-beam to mai beam
- Challenging task, similar to XFEL go

# Example Timing Tolerance

Plasma acceleration tends to give larger energy spreads for high beamloading

- E.g. O(3%) in PWFA with unshaped bunches and 50% efficiency (E. Adli)

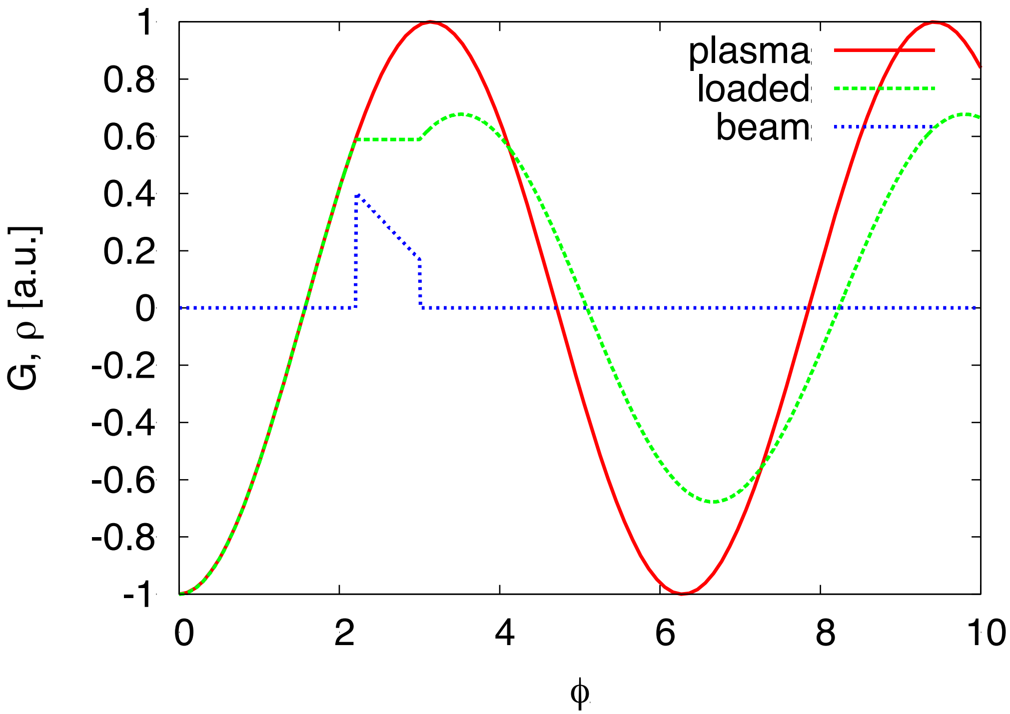
Need to

- Reduce energy spread (by bunch shaping?)
- Find better focus system (tough…)

Longitudinal bunch profile critical

⇒ Explicit design important to identify issues

⇒ In particular for shaped bunches




Plasma field varies along the bunch

For large beamloading this has to be O(G)

Use simple harmonic field of before

⇒ $10^{-3}$ gradient jitter equals 0.06°=O(0.01$\sigma_z$)

⇒ Very tight jitter tolerances for plasma accelerators O(10-200nm)

⇒ Detailed analysis seems important

Energy spread is critical limitation

Important to understand tolerances correctly

R&D programme essential on timing systems

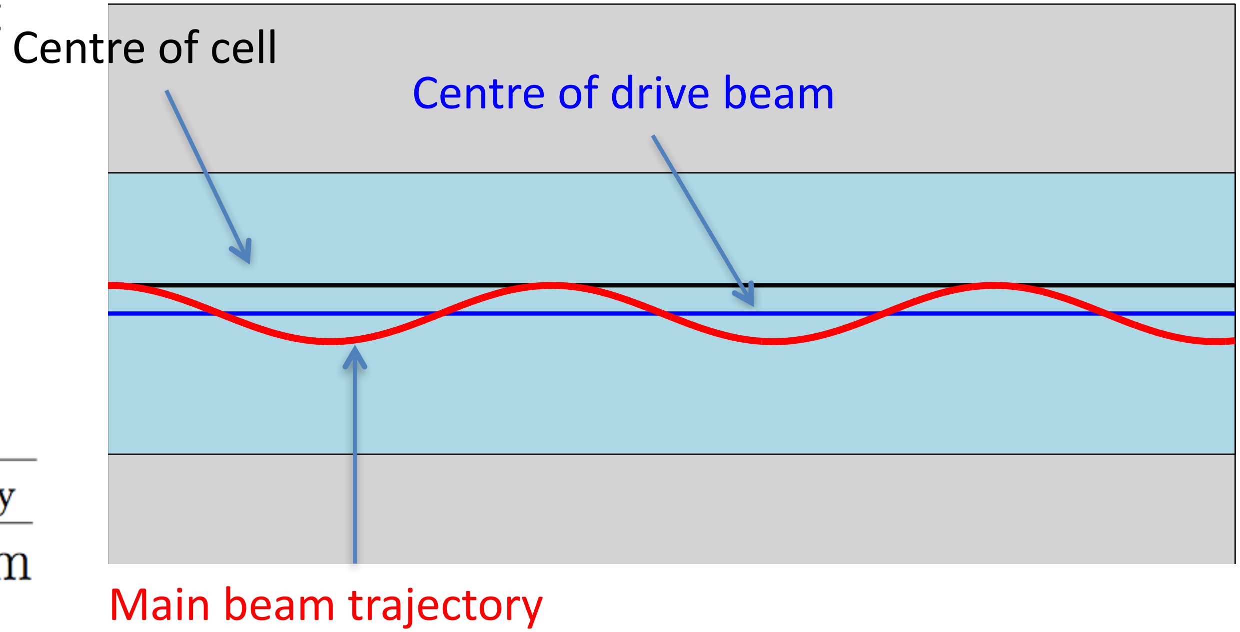
Current state of the art O(3000nm)

# Example Transverse Tolerance

First order estimate for middle part of cell

Laser or drive beam centre defines centre of the focusing

$$\sigma_y \approx 42\ \mathrm{nm} \left( \frac{\mathrm{GeV}}{\mathrm{E}} \frac{10^{16}\ \mathrm{cm}^{-3}}{\mathrm{n}_0} \right)^{\frac{1}{4}} \sqrt{\frac{\epsilon_\mathrm{y}}{\mathrm{nm}}}$$




PWFA beam at 1.5TeV has $\sigma_y$=O(30 nm) for $n_0=2\mathrm{x}10^{16}\mathrm{cm}^{-3}$

⇒ Beam jitter stability O(1 nm)?

⇒ Tough for laser/drive beam

⇒ Static misalignment is also critical

⇒ but depends on beam energy spread and tuning methods

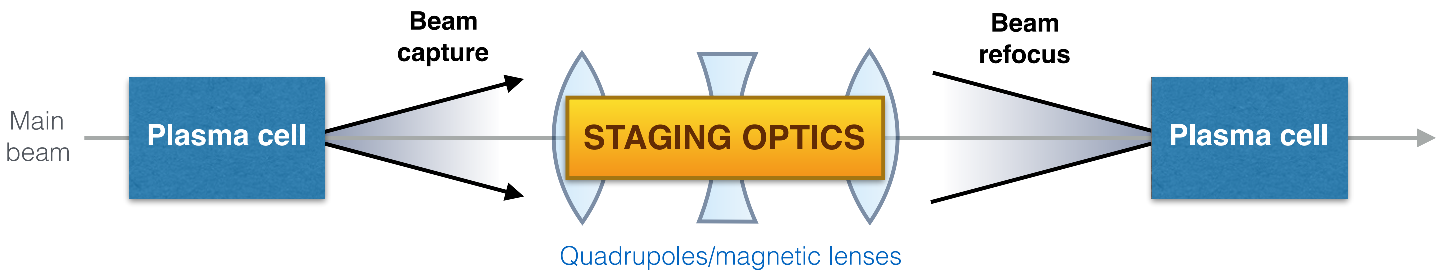
Important to understand tolerances correctly

R&D programme essential on transverse alignment and stabilisation

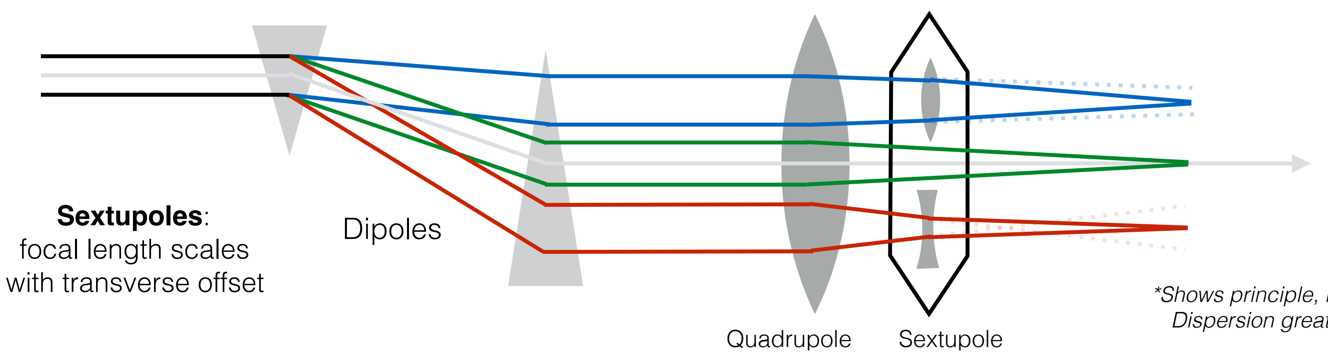
# Staging in PWFA/LWFA (the problem)

- Plasma/laser wakefield accelerators require staging to reach high energies.

- High acceleration gradient → Strong focusing
  → Highly diverging beams
  → Chromatic focusing errors give significant emittance growth.



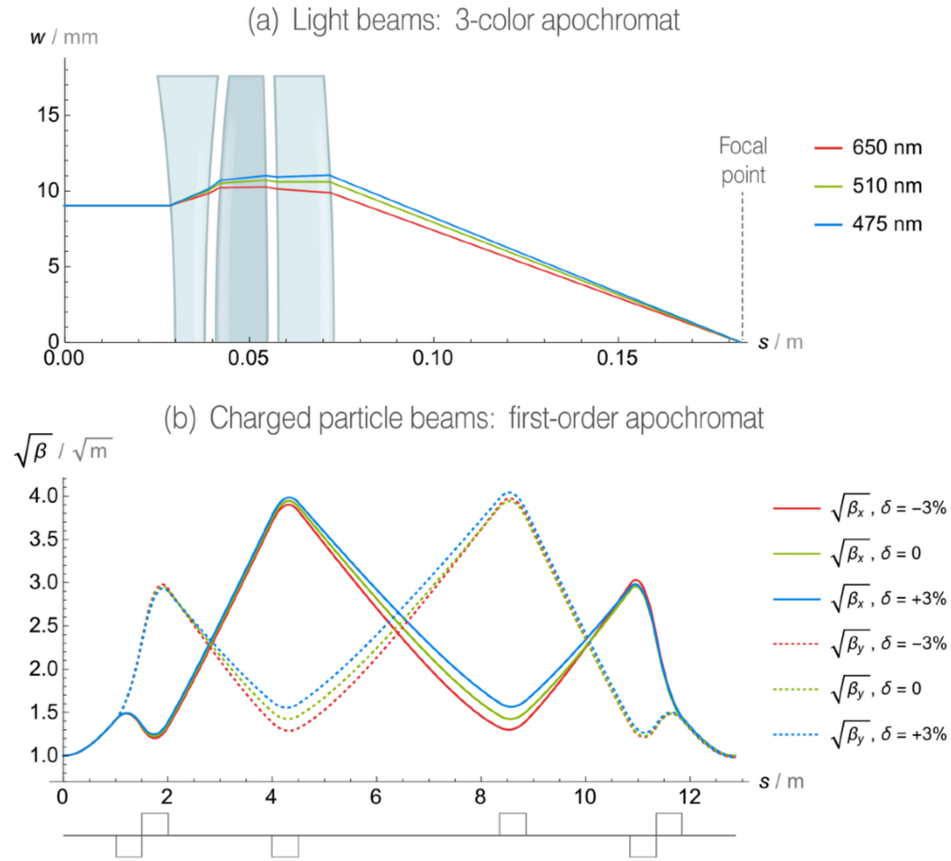

- Conventional chromatic correction uses **sextupoles in regions of large dispersion**: This introduces both **unwanted dispersion** as well as **synchrotron radiation from dipoles**.




**Shows principle, not realistic setup*
*Dispersion greatly exaggerated*

# Apochromatic correction (the solution)

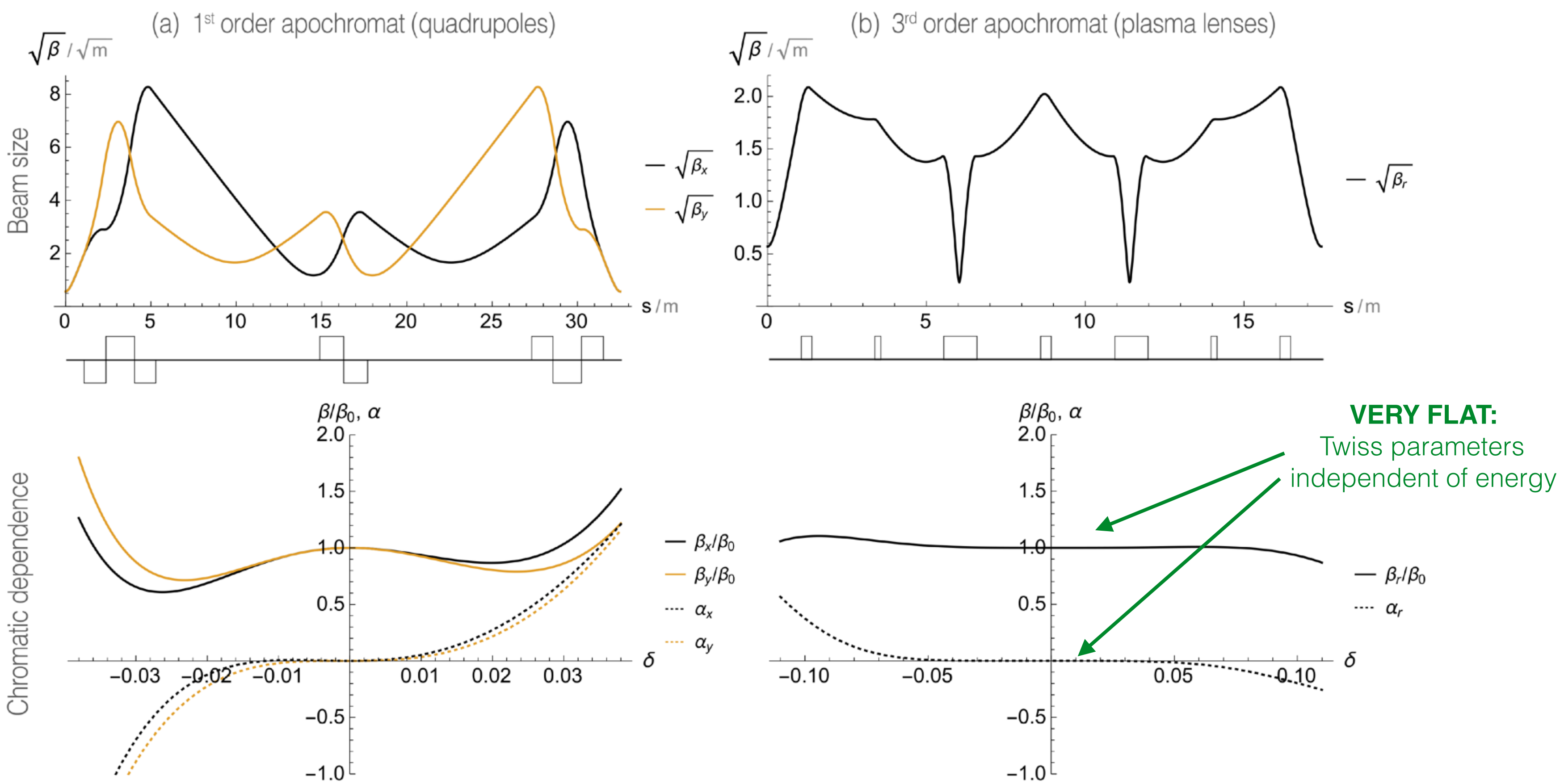
- Using **linear optics to correct chromatic focusing errors** at particular locations along the accelerator.
- Same method used in light optics (e.g. camera lenses).
- Relatively **new concept** in beam dynamics.
- We **recently published** the first peer-reviewed article on the topic in Physical Review Accelerators and Beams.




C. A. Lindstrøm & E. Adli,
"Design of general apochromatic drift-quadrupole beam lines",
Phys. Rev. Accel. Beams (19) 071002 (2016)

# Apochromatic plasma lens optics (our focus)

***Example:*** *100 GeV staging optics*




- **Plasma lenses are ideal** for apochromatic staging optics.
- Two reasons: **Radial symmetry** (halves d.o.f.) and **short focal length** (shorter L*)

# Agenda & Session Topics

Monday | Tuesday | Wednesday

| Start Time | Session Topic | Presentation | Presenter | Affiliation |
|---|---|---|---|---|
| 09:00 | Witness Injector | Witness Injector Motivation & 100MeV Option | Mark Hogan | SLAC |
| 10:00 | Witness Injector | Zig zag and peak current optimization | Vladimir Litvinenko | Stonybrook |
| 10:30 | | Break | | |
| 11:00 | Witness Injector | 4 GeV option | Joe Frisch | SLAC |
| 11:30 | Witness Injector | LWFA probe beam & witness injector option | Wei Lu | Tsinghua |
| 12:00 | | Lunch | | |
| 13:00 | Diagnostics | EOS optimization | Mike Litos | UC Boulder |
| 13:30 | Diagnostics | Hybrid linac-laser-plasma diagnostics and kicker | Bernhard Hidding | University of Strathclyde |
| 14:00 | Diagnostics | Energy Spectrometer & TCAV | Brendan O'Shea | SLAC |
| 14:30 | | Break | | |
| 15:00 | Diagnostics | FACET Diagnostic Experience | Nate Lipkowitz | SLAC |
| 15:30 | Diagnostics | E200/E225 quad scan experience | Sebastien Corde | Ecole Polytechnique |
| 16:00 | Diagnostics | E-217/E-210 experience (butterfly) | Navid Vafaei, Carl Lindstrom | Stonybrook University, University of Oslo |
| 16:30 | Diagnostics | Prospects for crystal channels | Brendan O'Shea | SLAC |
| 16:50 | Diagnostics | Discussion | All | |
| 17:20 | | Adjourn | | |

Add new item