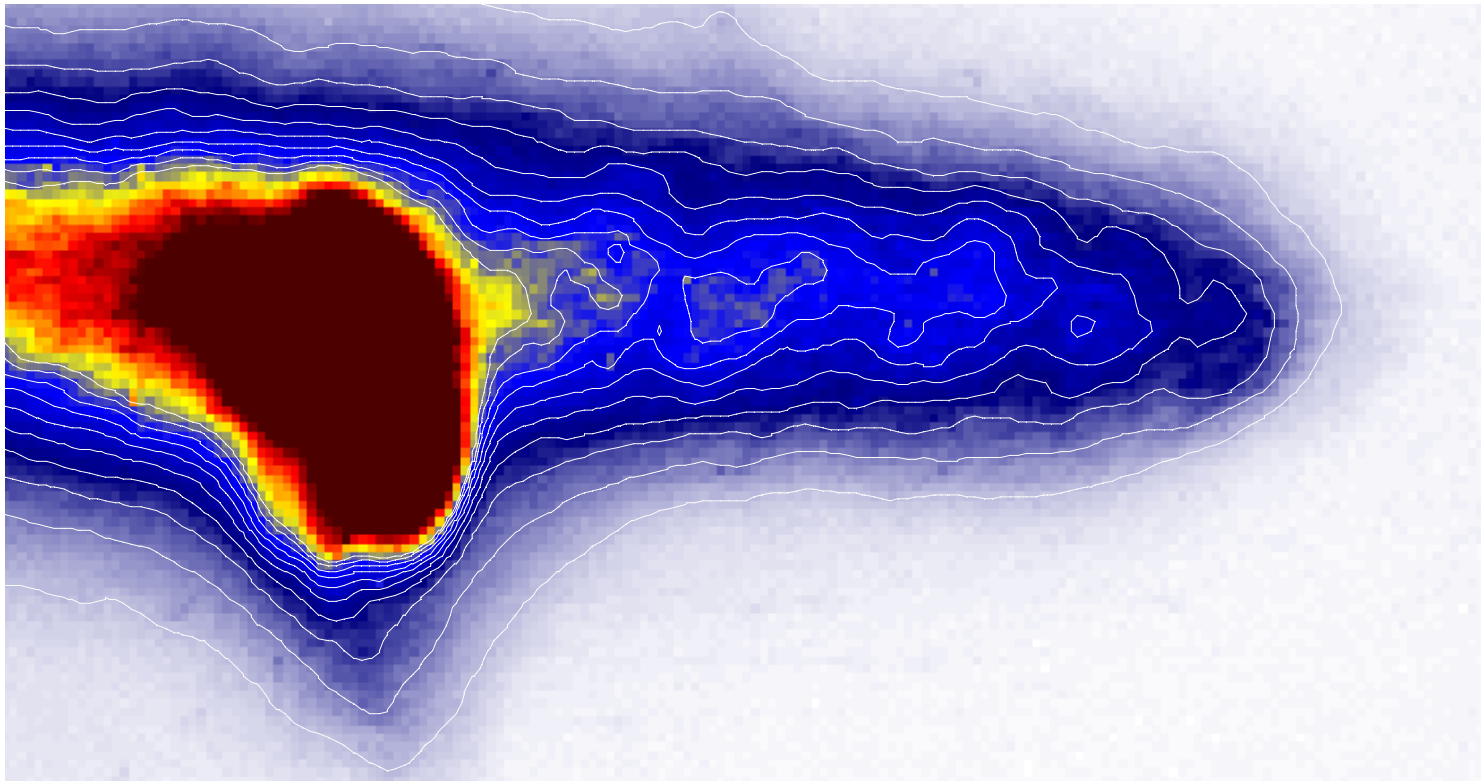
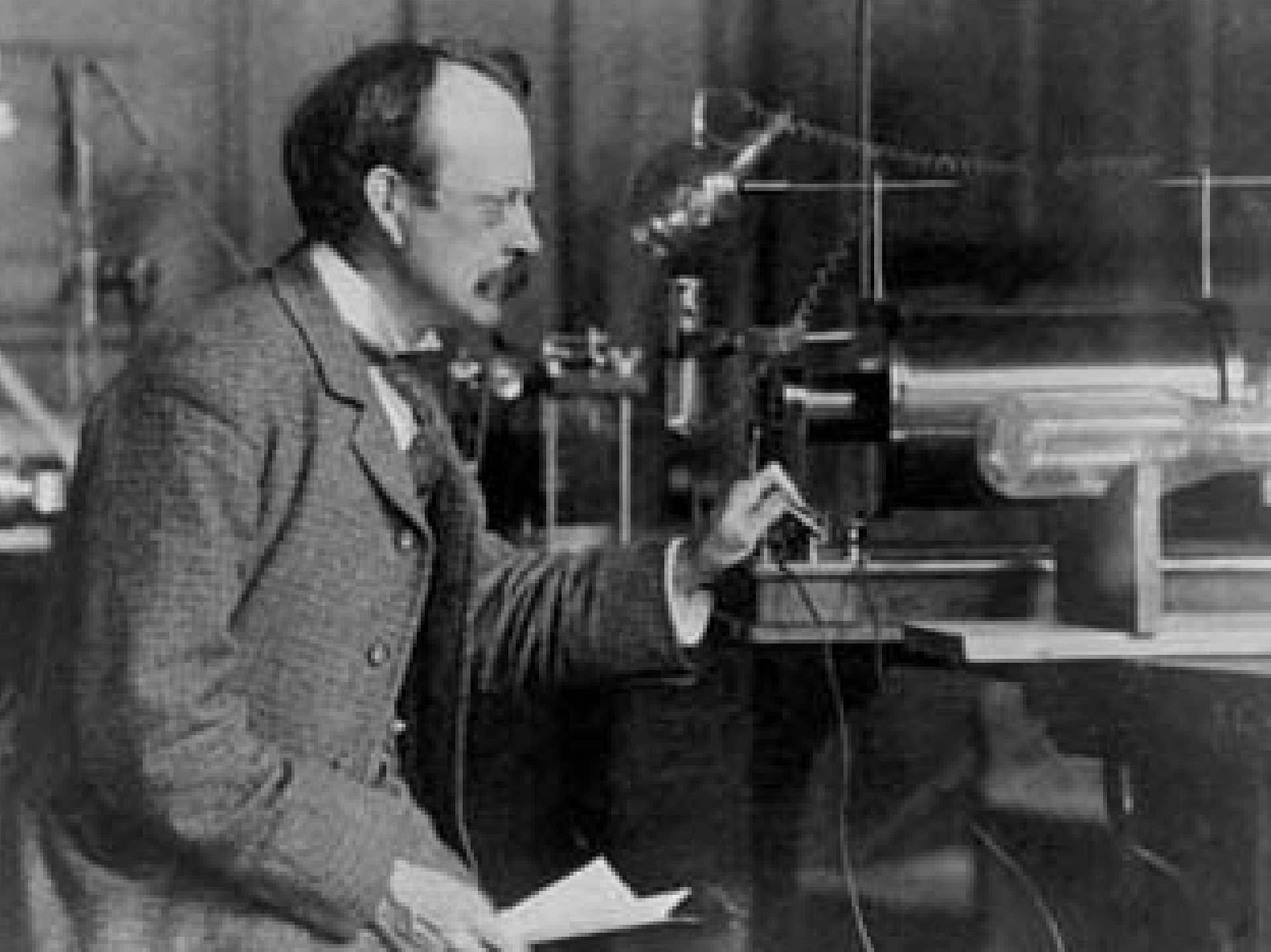


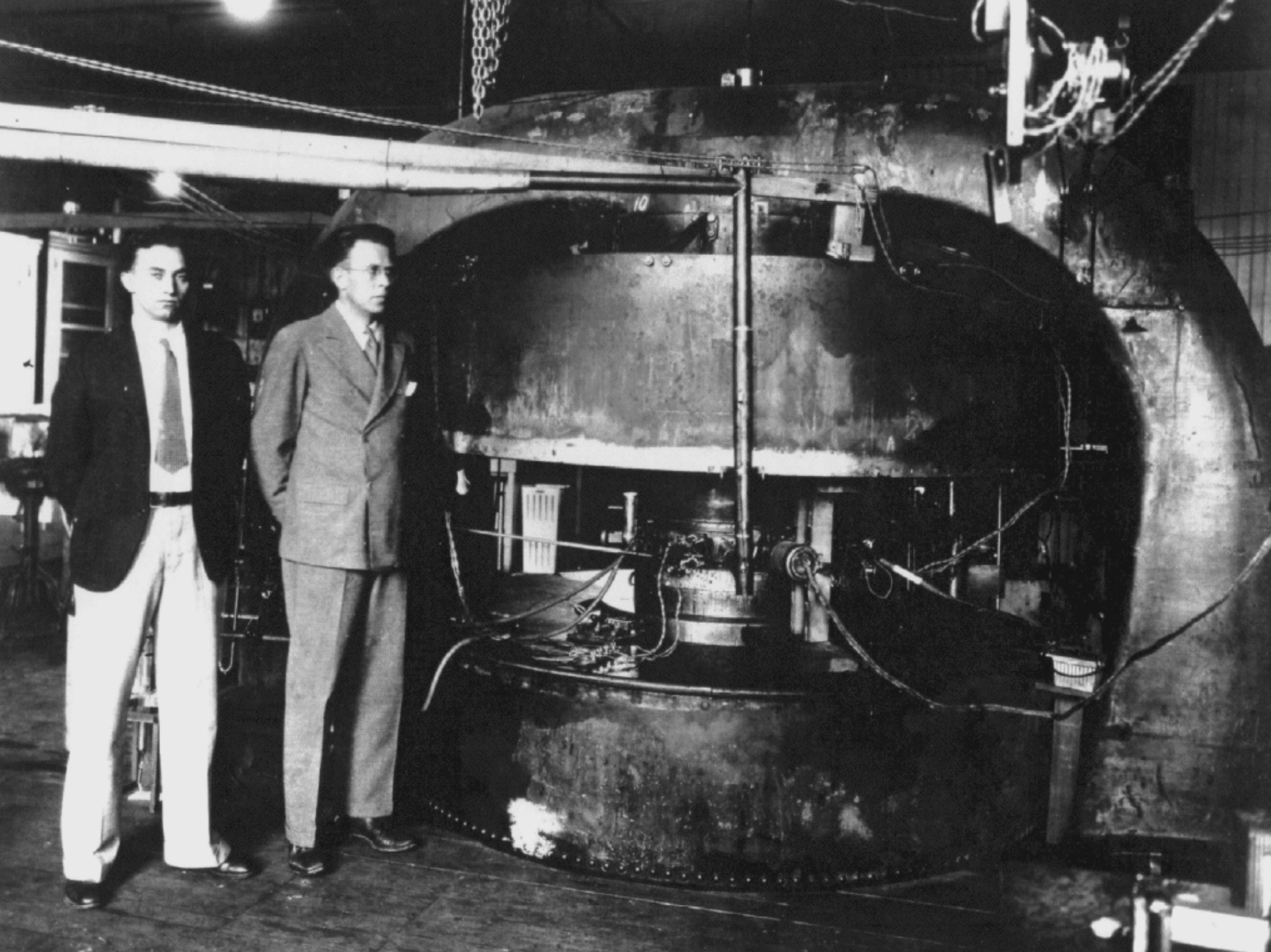
# Energy Doubling of 42 GeV Electrons

Rasmus Ischebeck, for the E-167 Collaboration



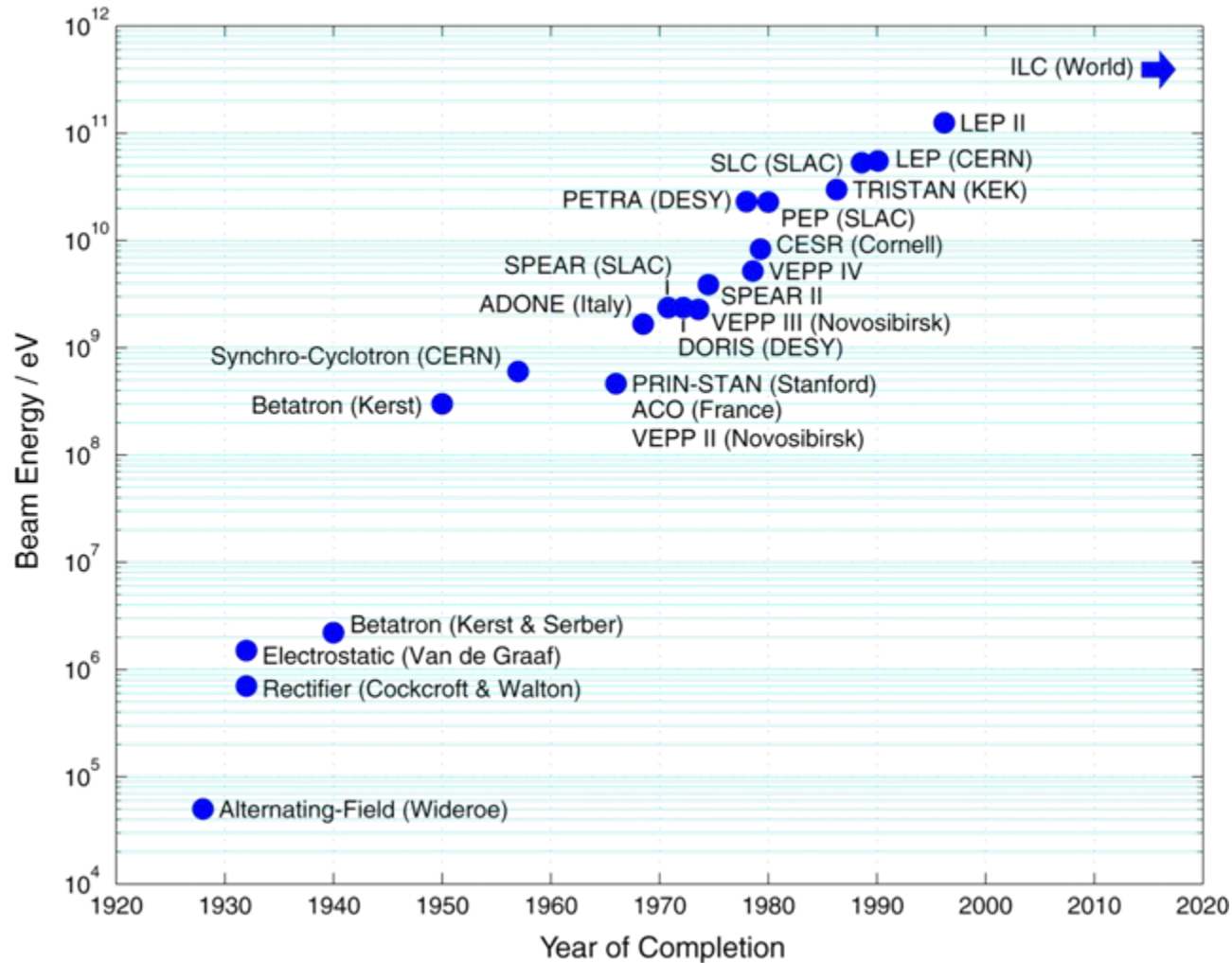




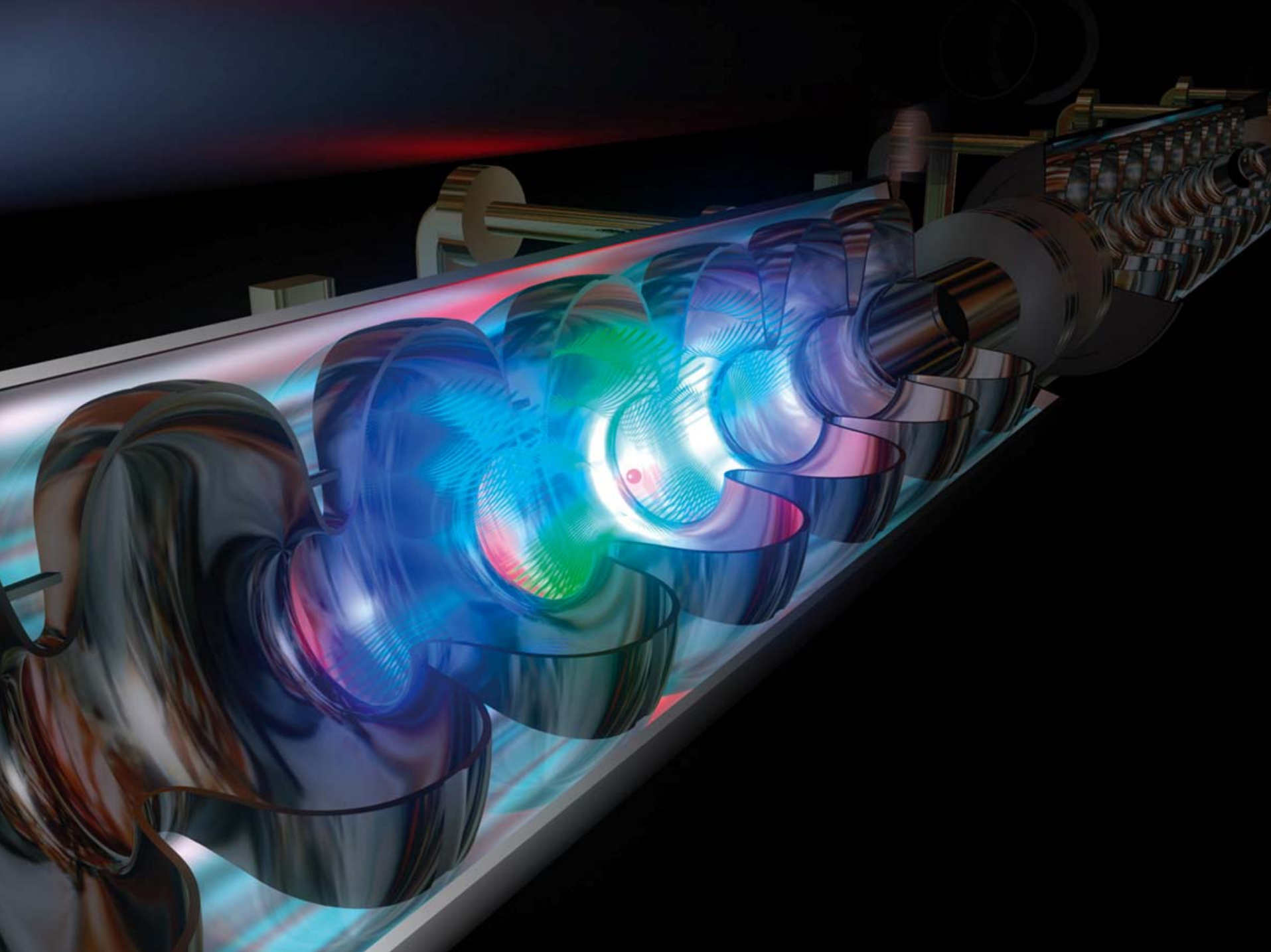




# Evolution of Electron Accelerators (Livingston Plot)





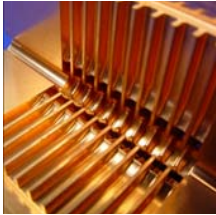


# Basic Requirements for Electron Accelerators beyond ILC

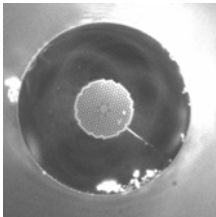
- Energy  $W \gtrsim 5 \text{ TeV}$   $W = E \cdot e \cdot L$  (Linac)
- Luminosity  $\mathcal{L} \gtrsim 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$   $\mathcal{L} = \frac{N^2 f}{4\pi \sigma_x \sigma_y}$
- ⇒ Beam power  $P \approx 100 \text{ MW}$   $P = U \cdot I$
- Cost  $C \lesssim 5 \cdot 10^9$
- High accelerating fields
- Low emittance (small diameter)
- High bunch charge
- Good efficiency

# Advanced Accelerator Technologies

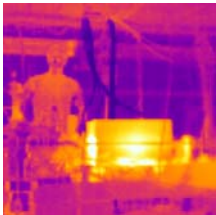
- In linear accelerators, the energy is determined by the achievable accelerating fields:
  - 20 MV/m (SLAC Linac)
  - 35 MV/m (ILC)
- Options for higher accelerating fields:



- RF structures at higher frequencies
  - about 300 MV/m



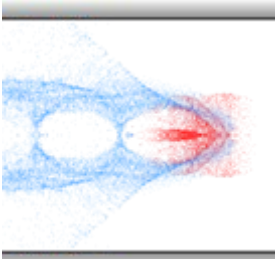
- Dielectric structures at optical frequencies
  - about 1 GV/m



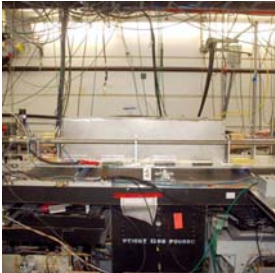
- Non-linear plasma wakes
  - about 50 GV/m

# Energy Doubling of 42 GeV Electrons

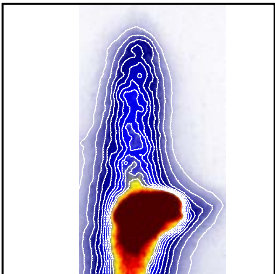
Rasmus Ischebeck, for the E-167 collaboration



- Plasma Wakefield Acceleration



- Experimental Setup



- Results

# Plasma Wakes – Theory

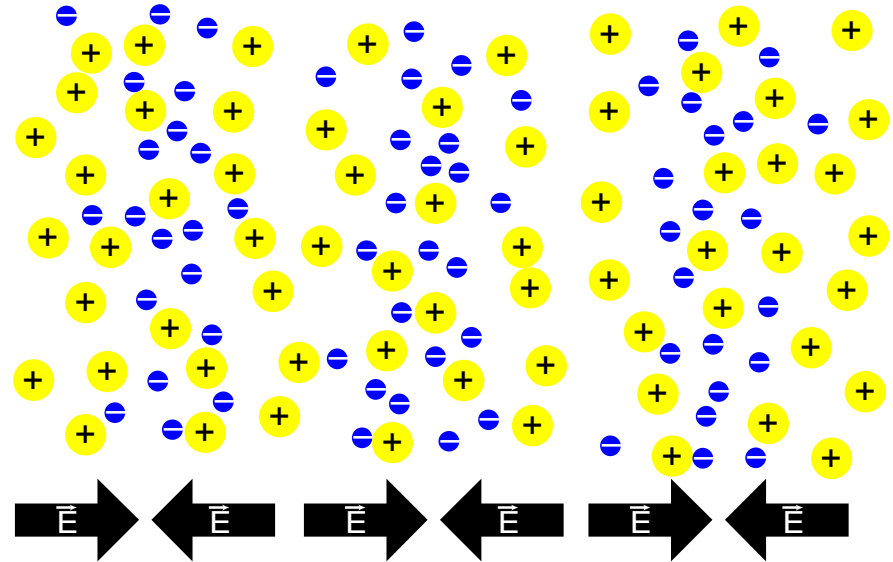
- Unlike electromagnetic waves in vacuum, plasma wakes can have a longitudinal electric field
- Linear plasma wake:

- Limit: 
$$\lambda_p \approx \sqrt{\frac{10^{15} \text{cm}^{-3}}{n_p}} \text{ mm}$$

$$E_0 = \frac{4\pi \epsilon_0 c m_e}{e} \omega_p \approx \sqrt{\frac{n_p}{\text{cm}^{-3}}} \frac{\text{V}}{\text{cm}}$$

# Plasma Wakes – Theory

- In conventional accelerators, resonant cavities are used to generate an electromagnetic field with longitudinal E component
- The achievable field is determined by the cavities
- Plasma waves have a longitudinal electric field



- Linear plasma wake:

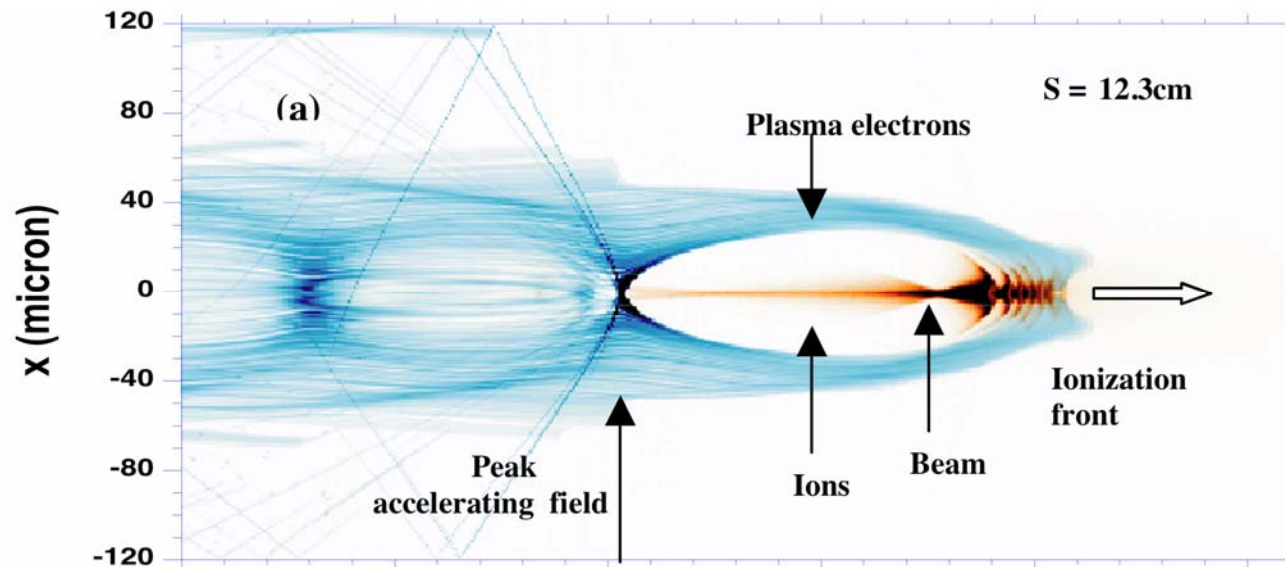
$$\lambda_p \approx \sqrt{\frac{10^{15} \text{cm}^{-3}}{n_p}} \text{ mm}$$

- Limit:

$$E_0 = \frac{4\pi \varepsilon_0 c m_e}{e} \omega_p \approx \sqrt{\frac{n_p}{\text{cm}^{-3}}} \frac{\text{V}}{\text{cm}}$$

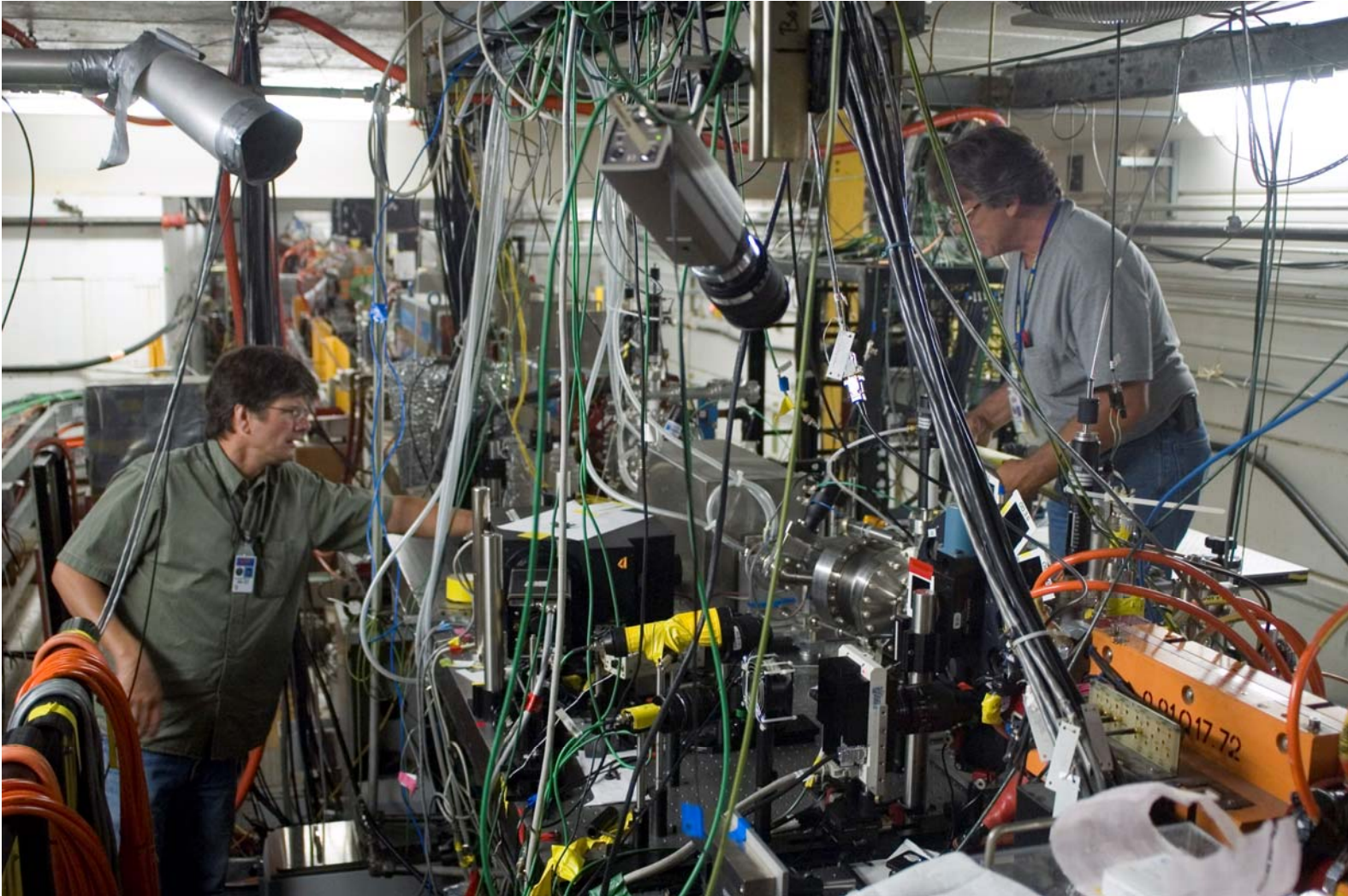
# Plasma Wakes – Theory

- Above this limit: non-linear wakes, “Blow-out regime”
- Fields can be calculated only with numerical methods



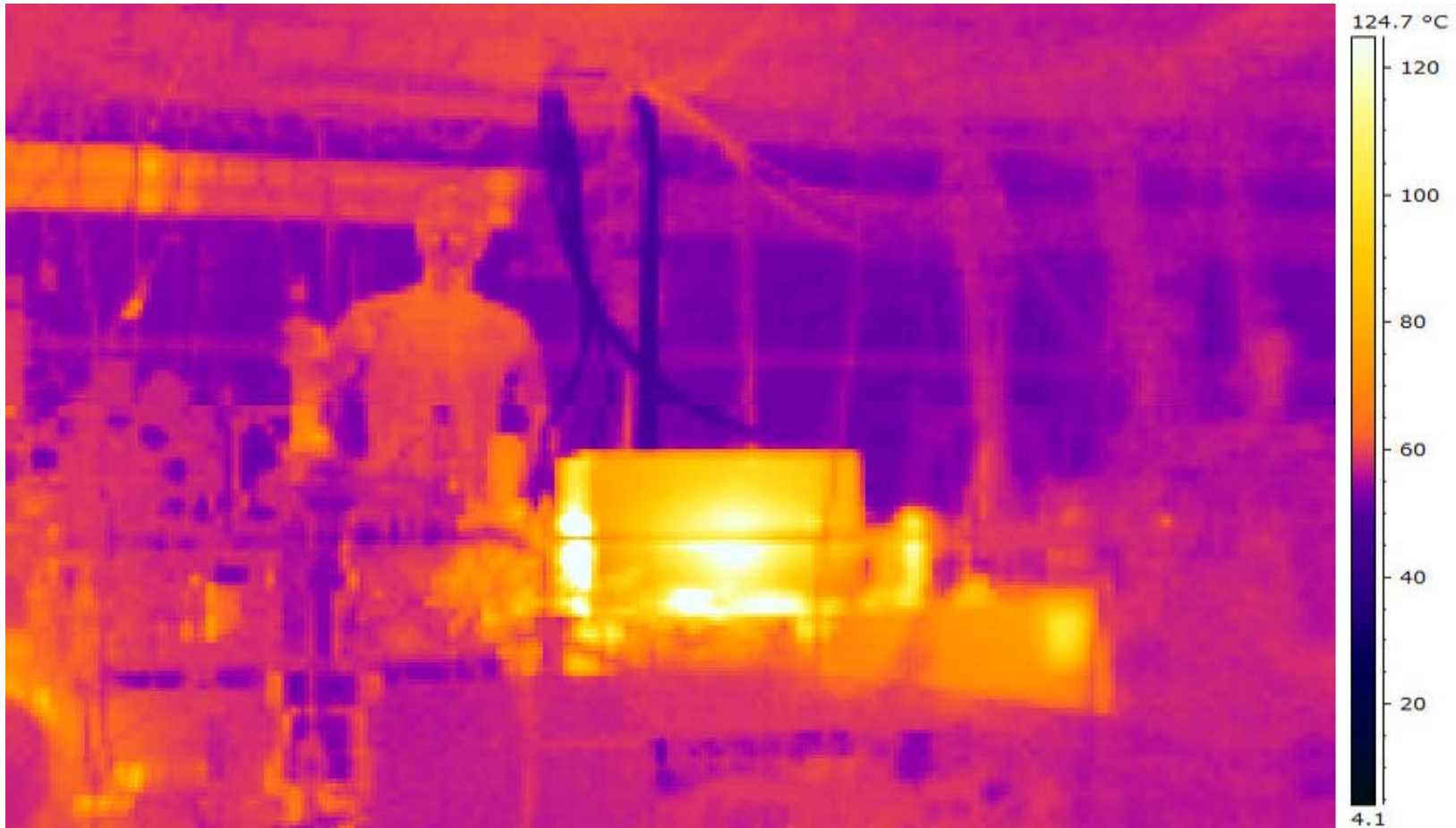
- Typical wavelength: 50  $\mu\text{m}$
- Accelerating fields up to 50GV/m

# Plasma Wakes – Reality



Rasmus Ischebeck, Energy Doubling of 42 GeV Electrons. Max-Planck-Institut für Quantenoptik, 2007-09-18

# Plasma Wakefield Acceleration

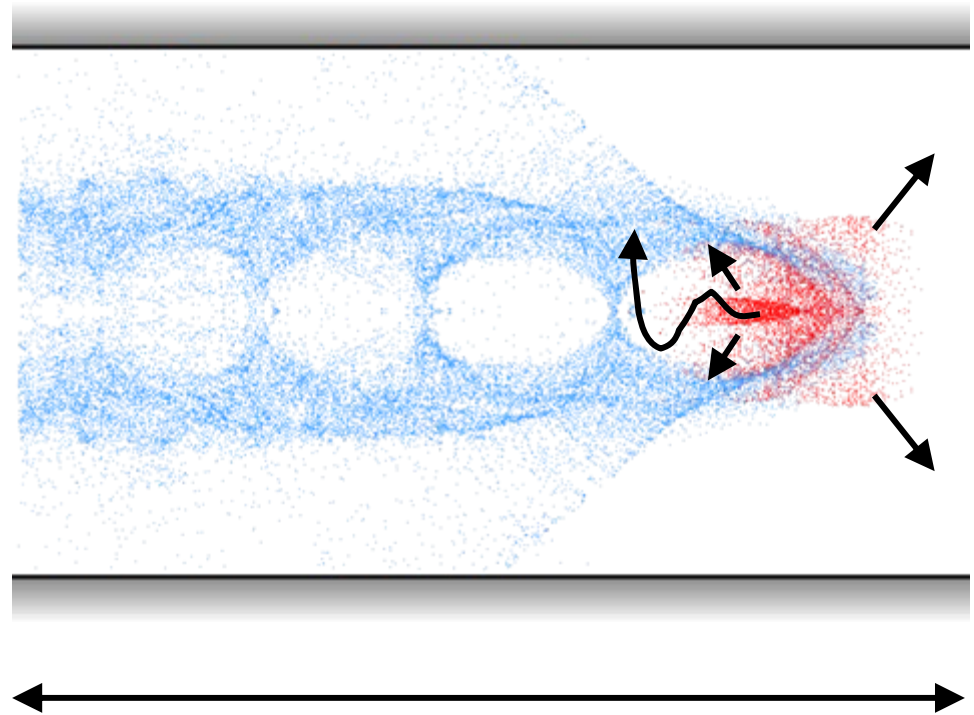


# Plasma Wakefield Acceleration



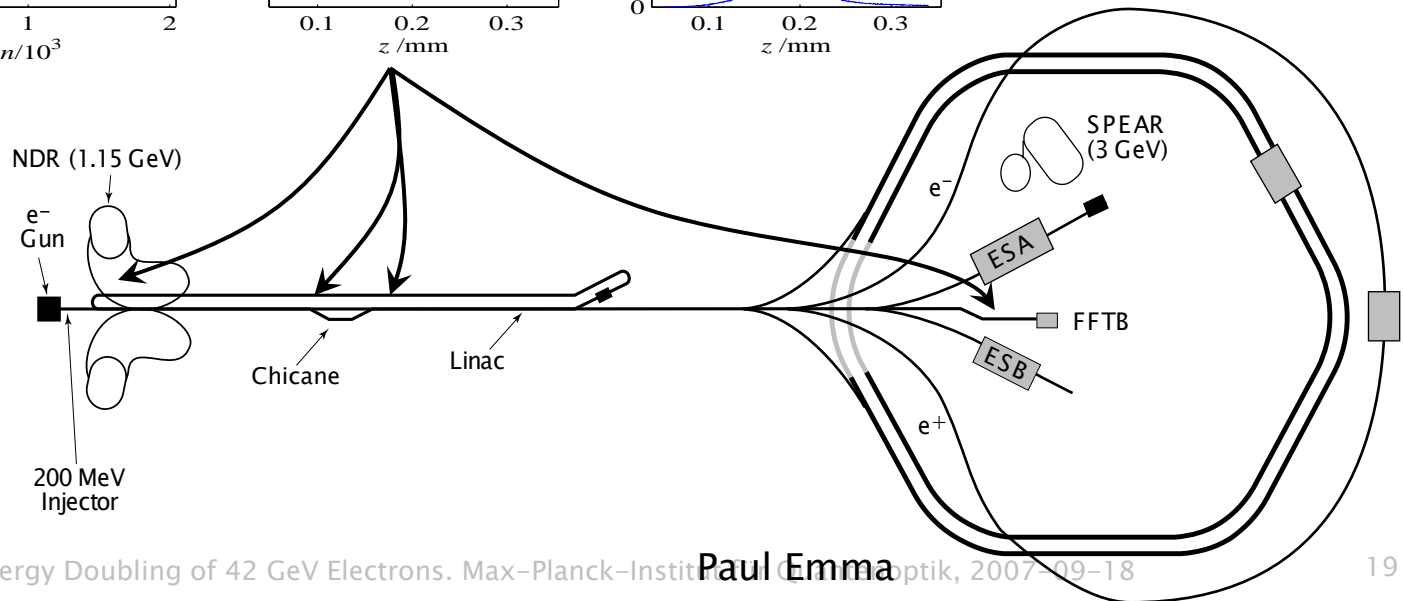
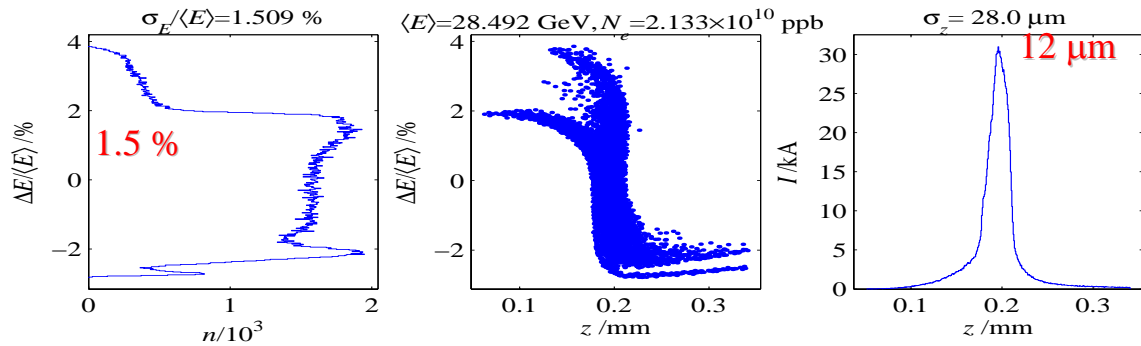
# What Determines the Maximum Energy?

- Plasma length
  - Oven length
  - Head erosion
- Hose instability
- Mobile ions
- Energy depletion of the drive beam (transformer ratio)

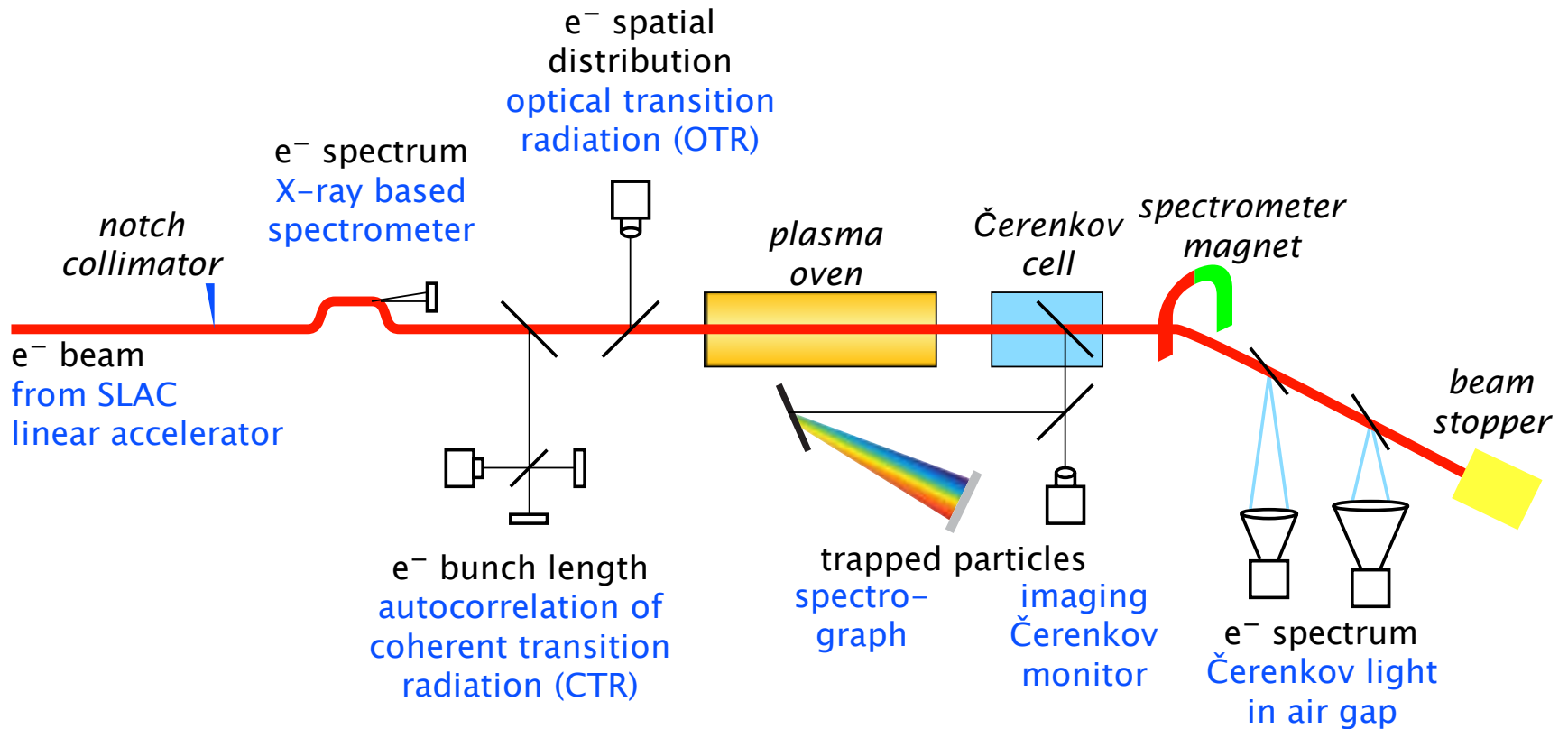


# Plasma Acceleration at SLAC

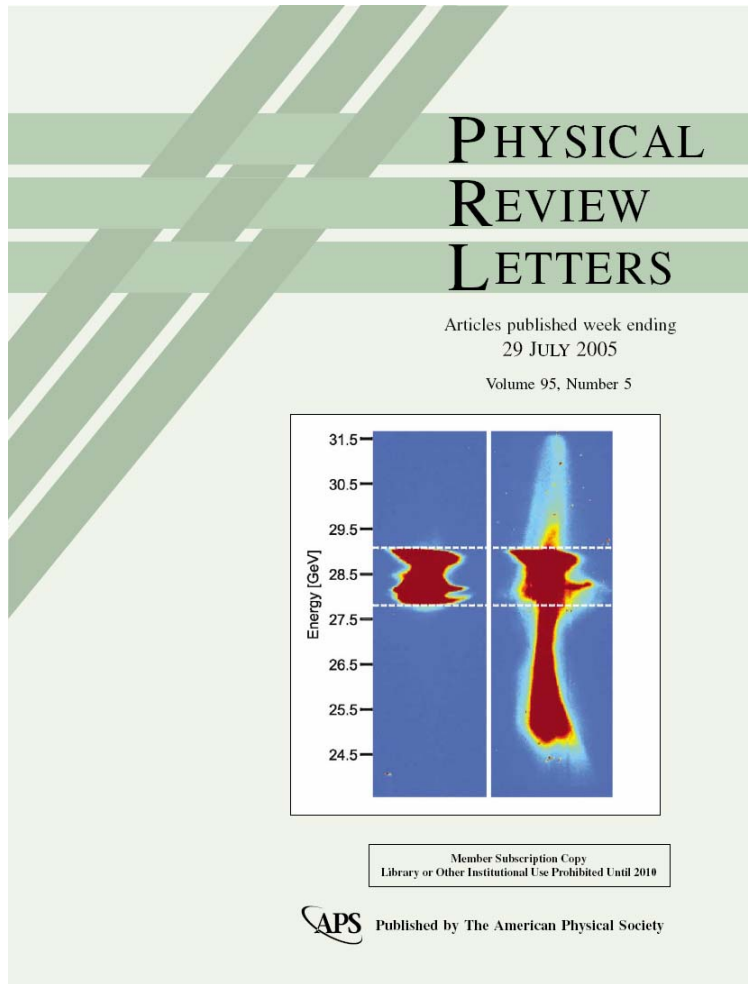
Acceleration, compression and focusing to a peak power density of 5 YW/m<sup>2</sup>



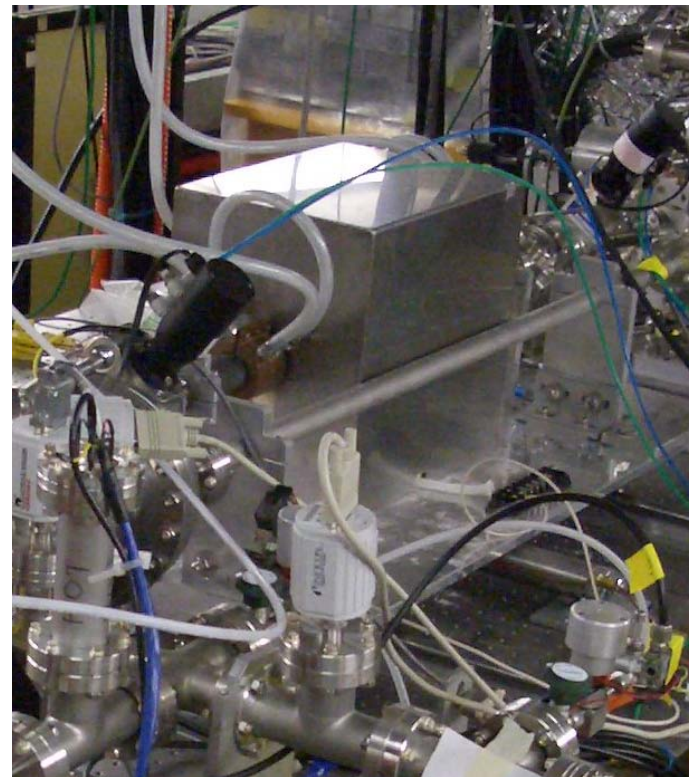
# Experimental Setup: E-167



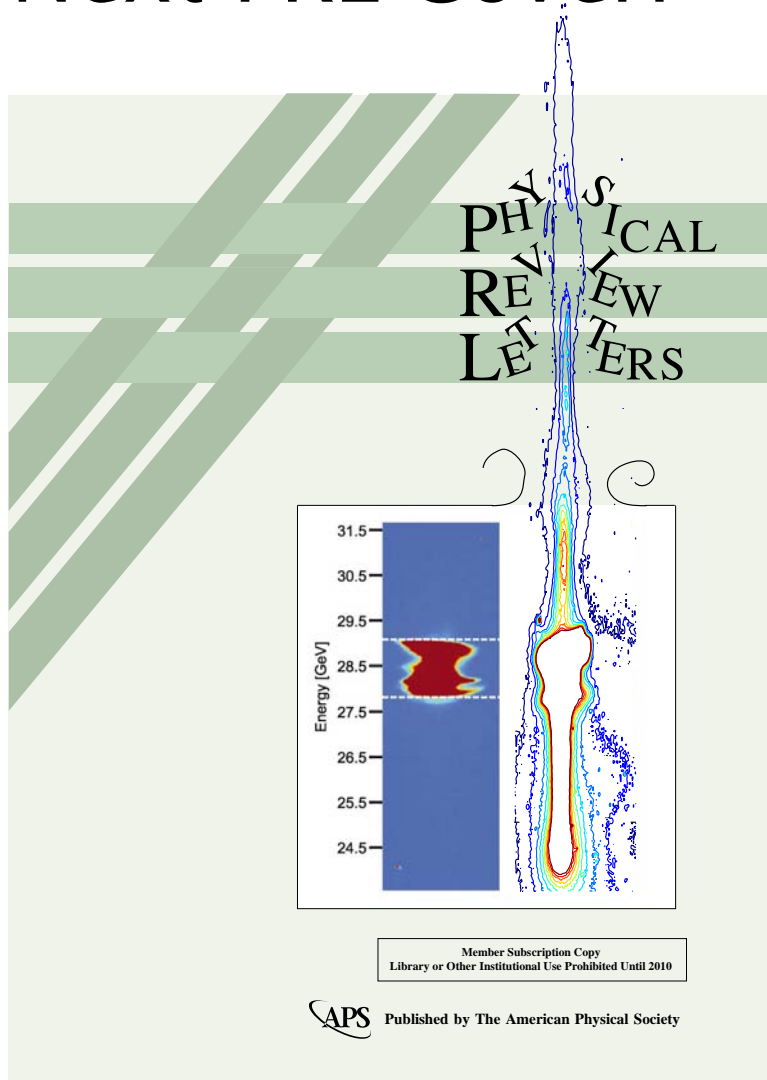
# Previous Results



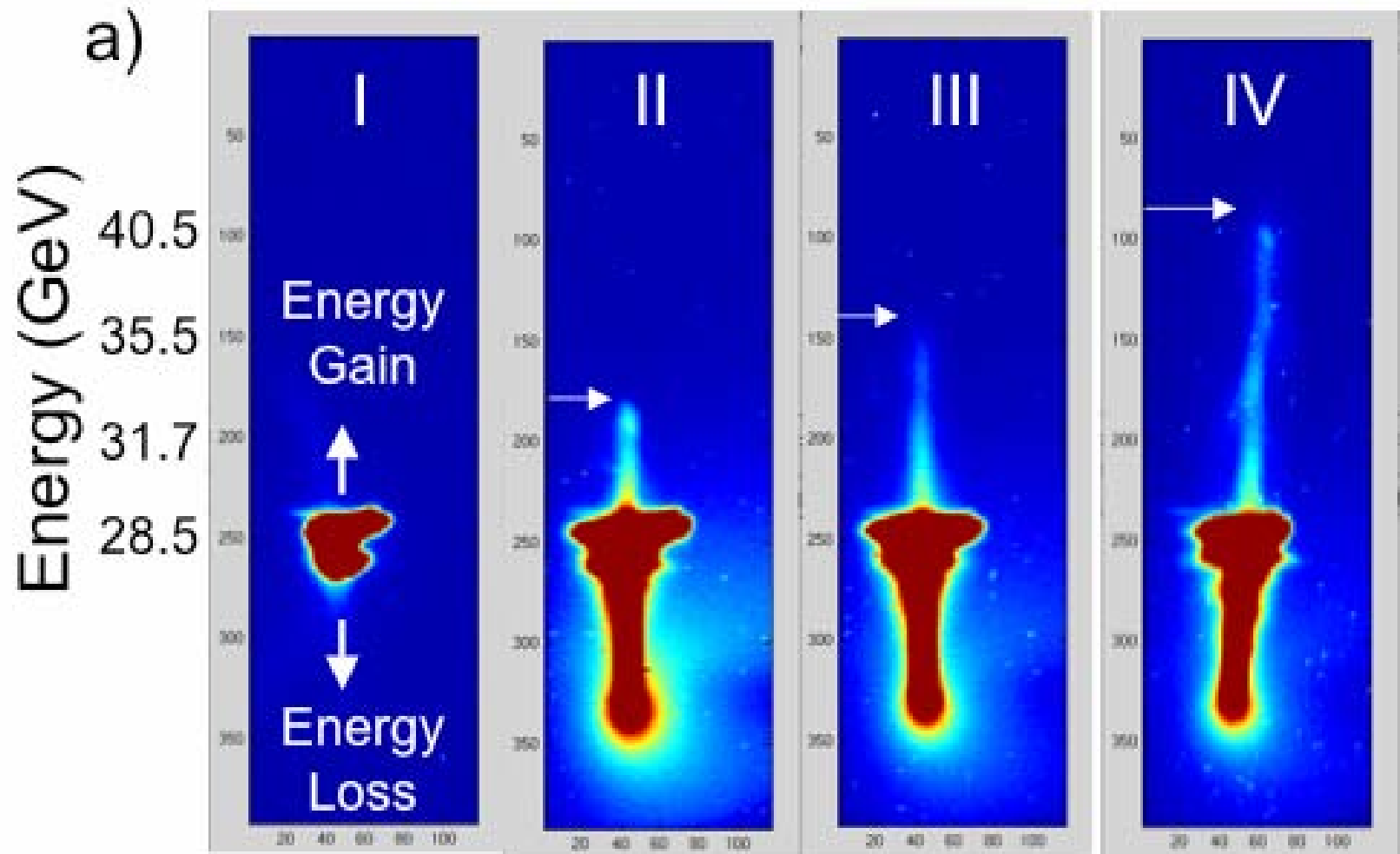
More than 3 GeV energy gain  
in 10 cm plasma length



# Next PRL Cover?

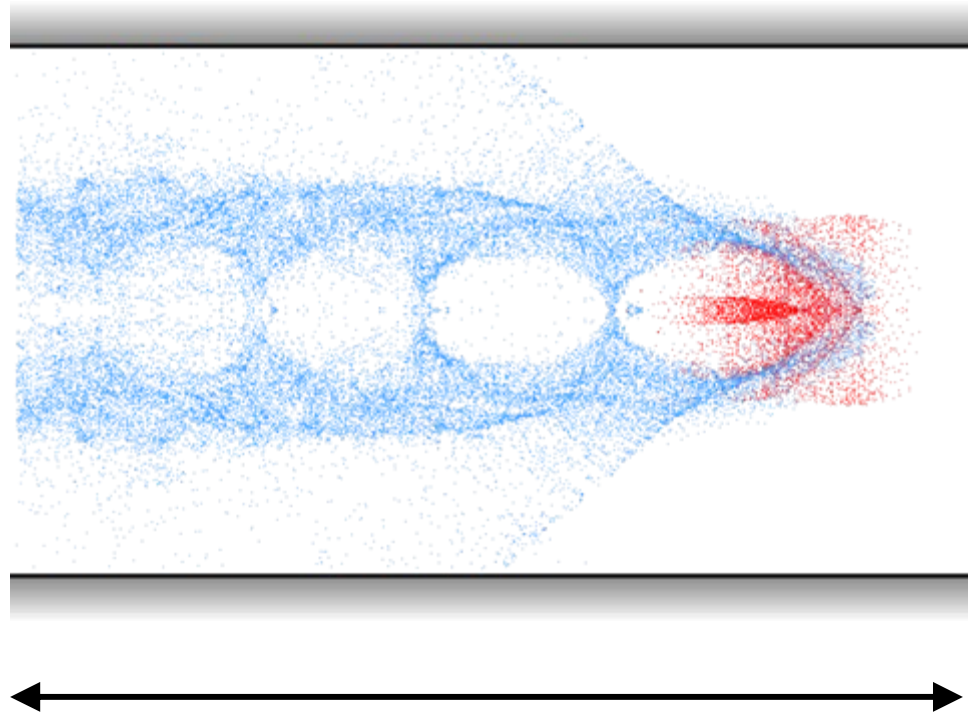


# Increasing the Plasma Length to 30.5 cm



# What Determines the Maximum Energy?

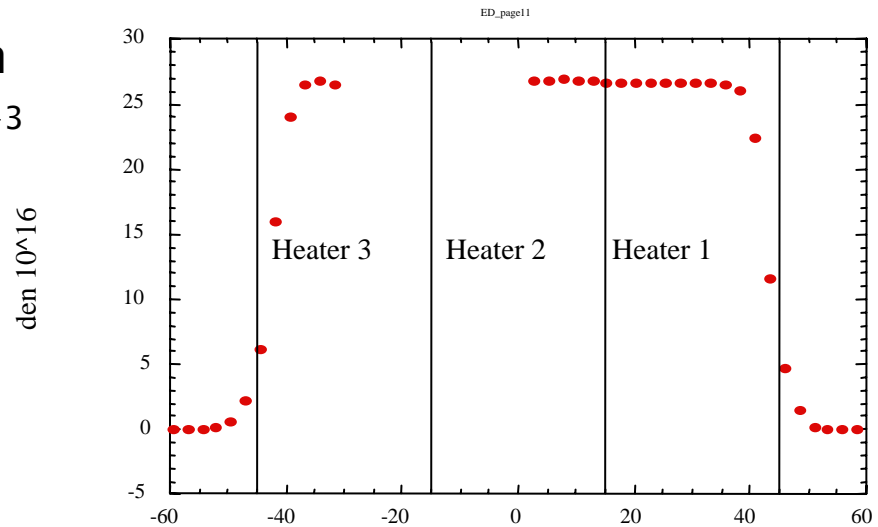
- Plasma length
  - Oven length
  - Head erosion
- Hose instability
- Mobile ions
- Energy depletion of the drive beam (transformer ratio)



# Build New Plasma Oven



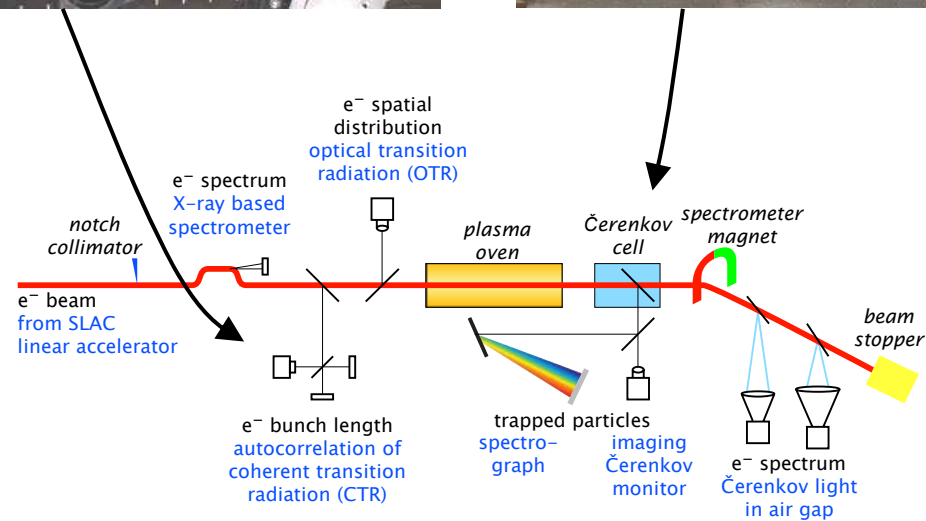
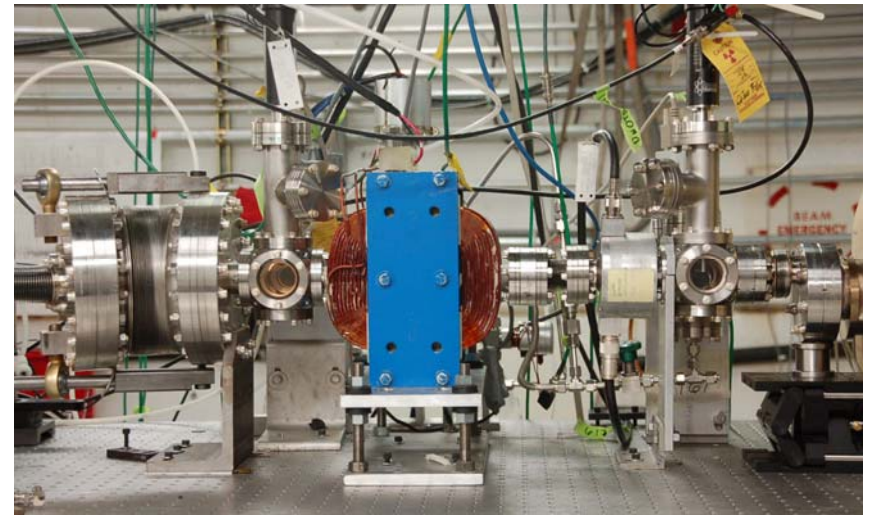
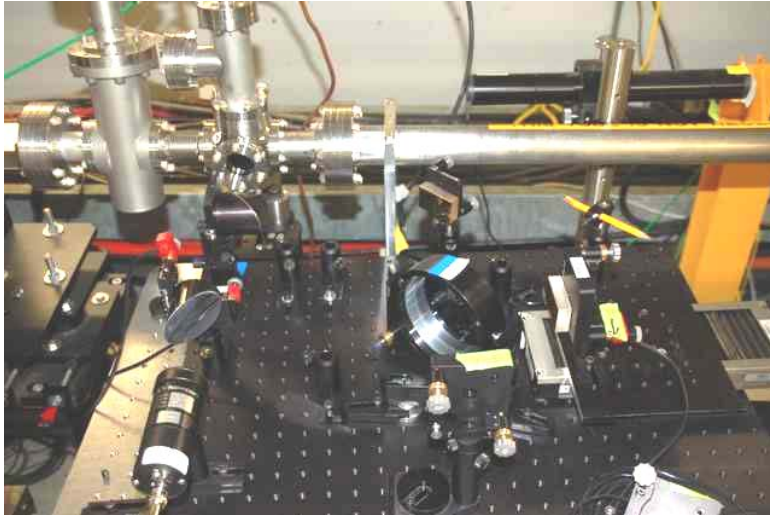
- Up to 1.13 m plasma length
- Plasma density:  $3 \cdot 10^{17} \text{ cm}^{-3}$



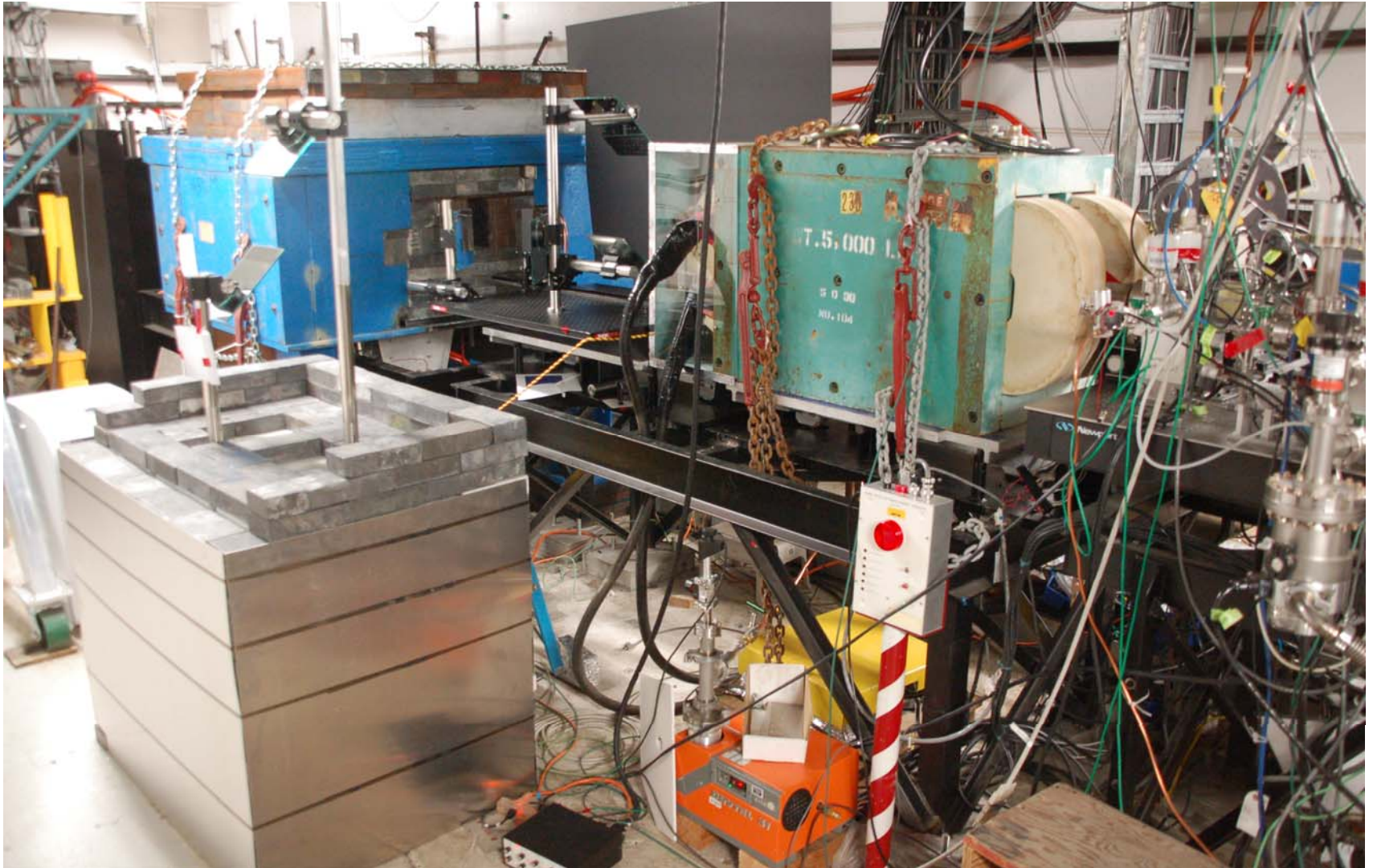
# More Energy in the Drive Beam



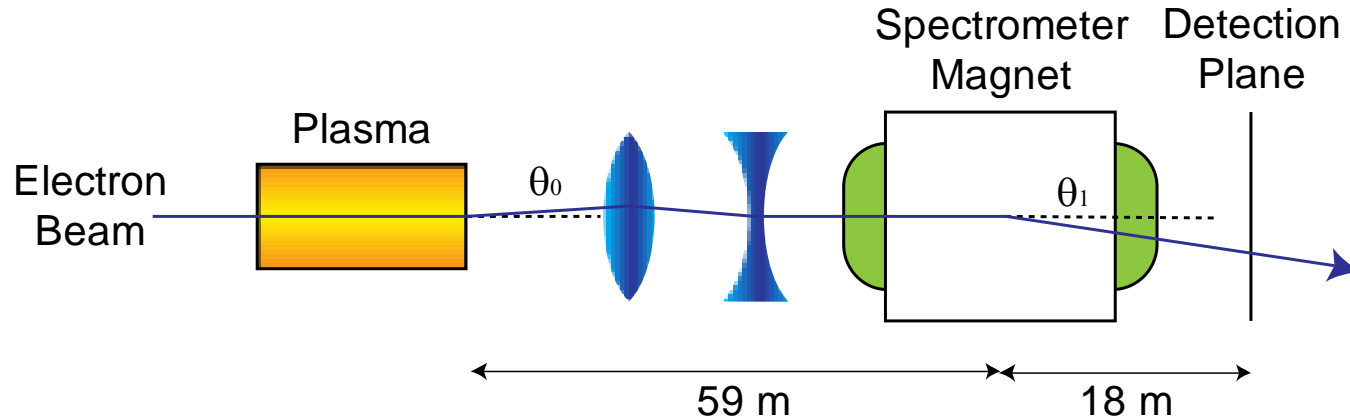
# More Diagnostics



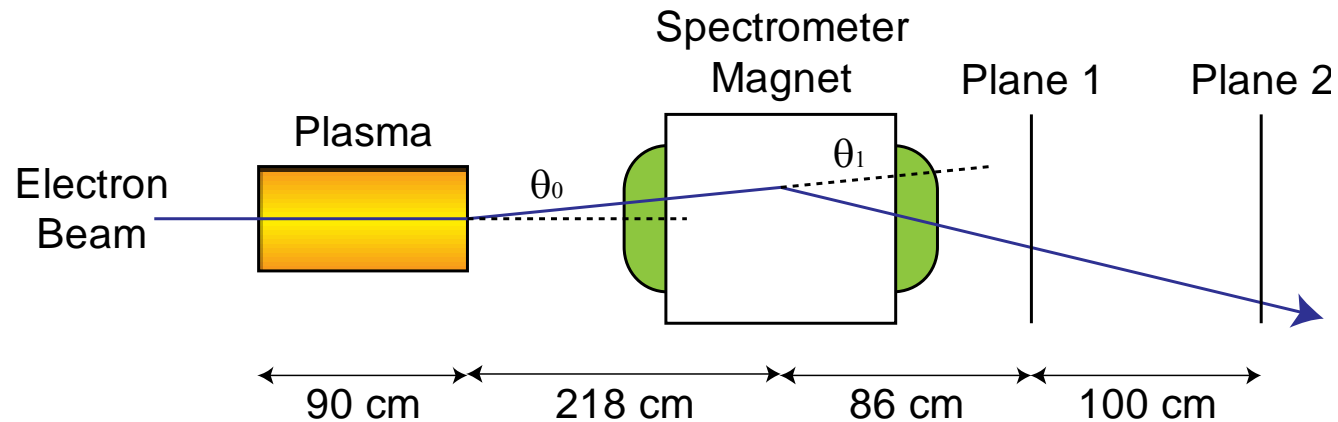
# New Spectrometer



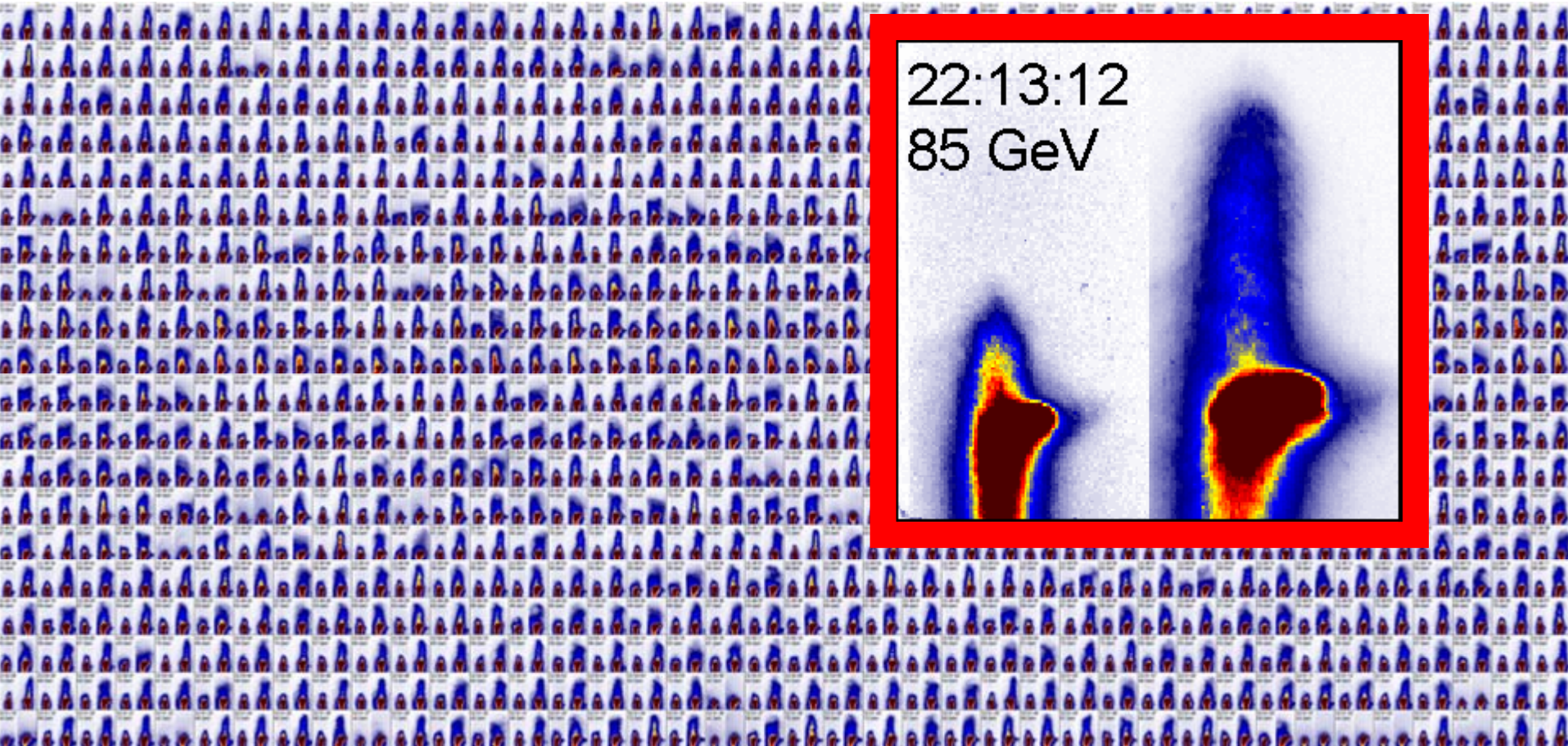
# Imaging Spectrometer



# Two-Plane Spectrometer

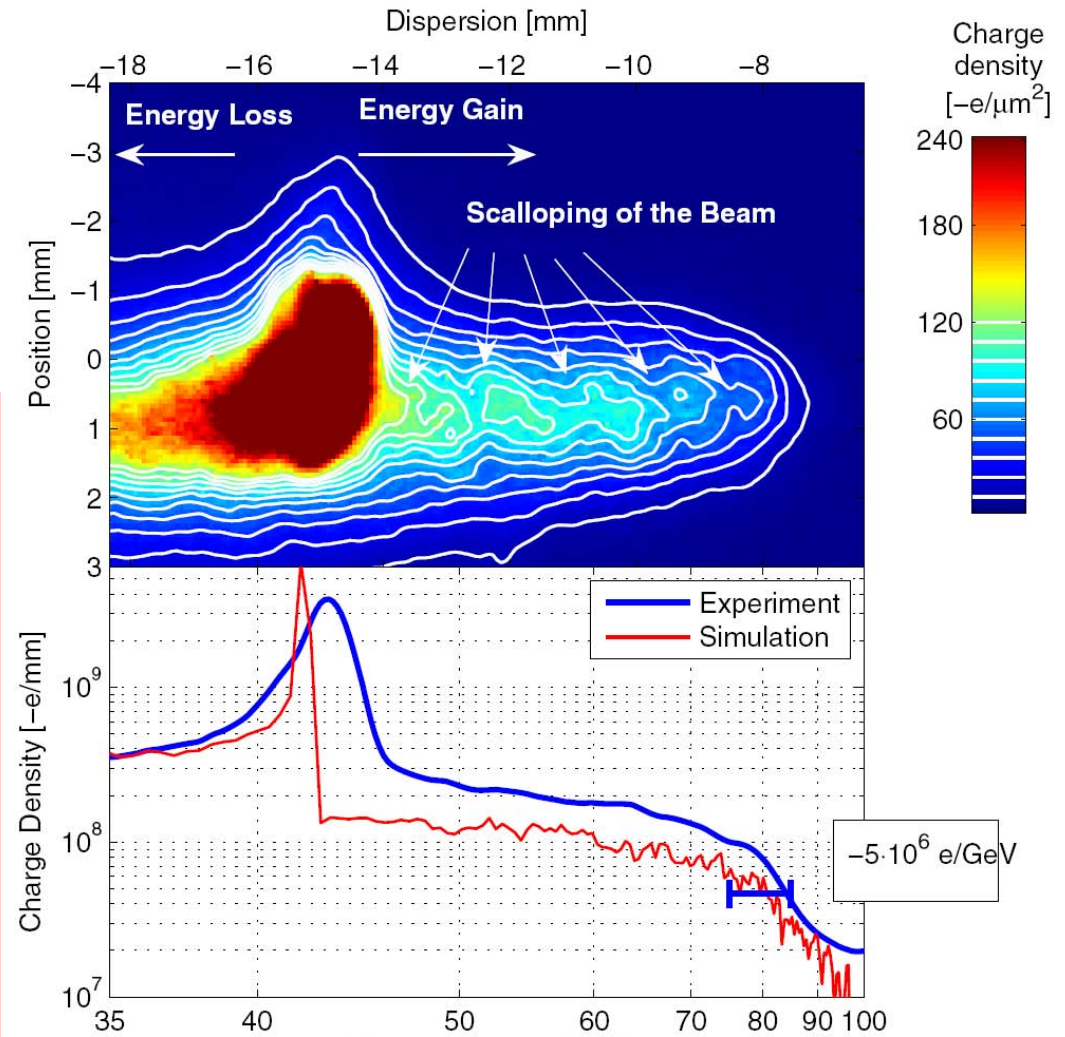
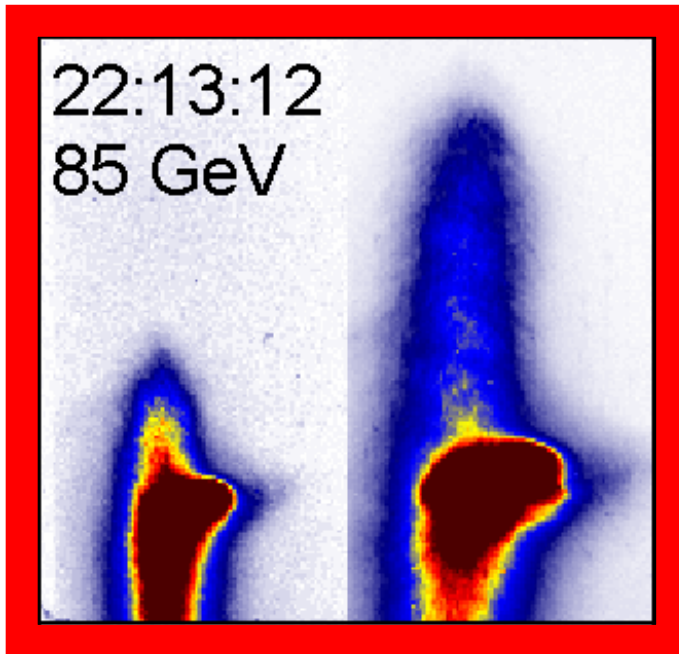


# Images Recorded in the Two Planes 800 Consecutive Events

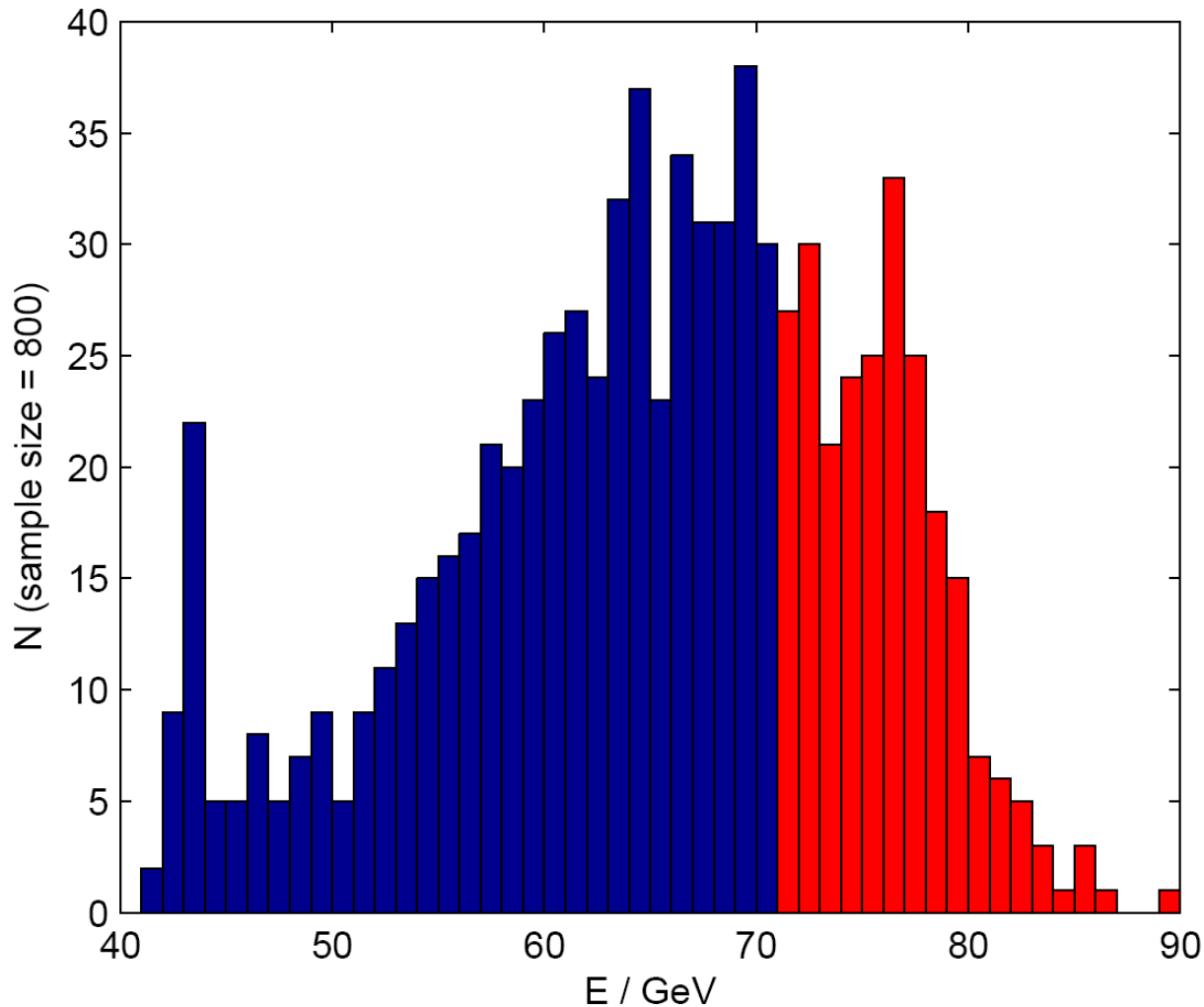


# Energy Doubling

- Plasma length: 85 cm
- Density:  $2.7 \cdot 10^{17} \text{ cm}^{-3}$
- Incoming energy: 42 GeV
- Peak energy: 85 GeV



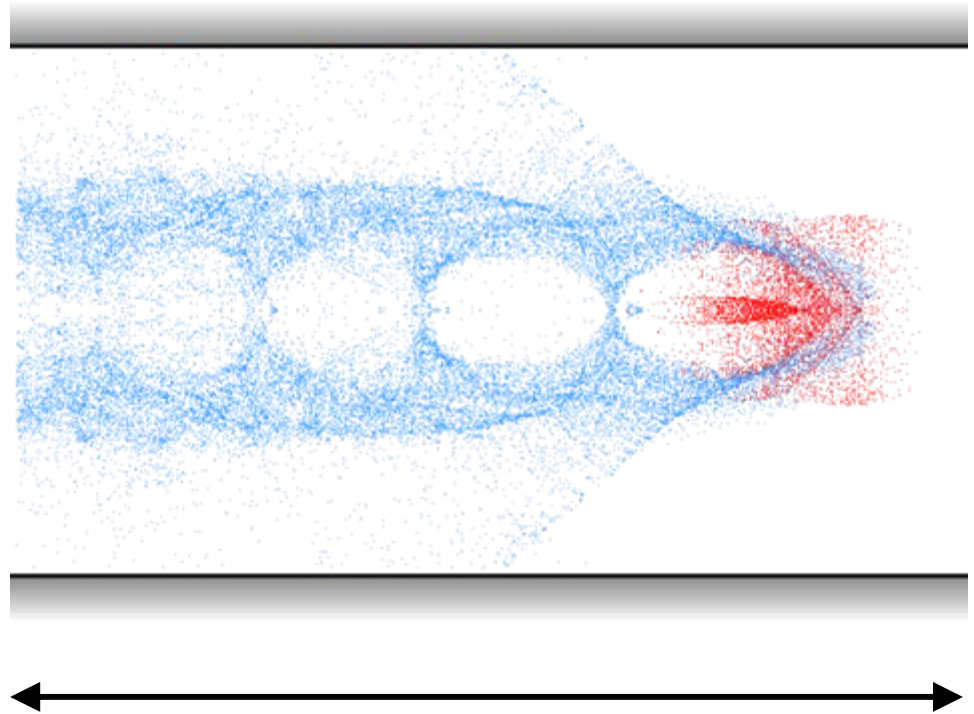
# Peak Energy in 800 Events



$\geq 30$  GeV  
peak energy gain  
in more than 30%  
of the events

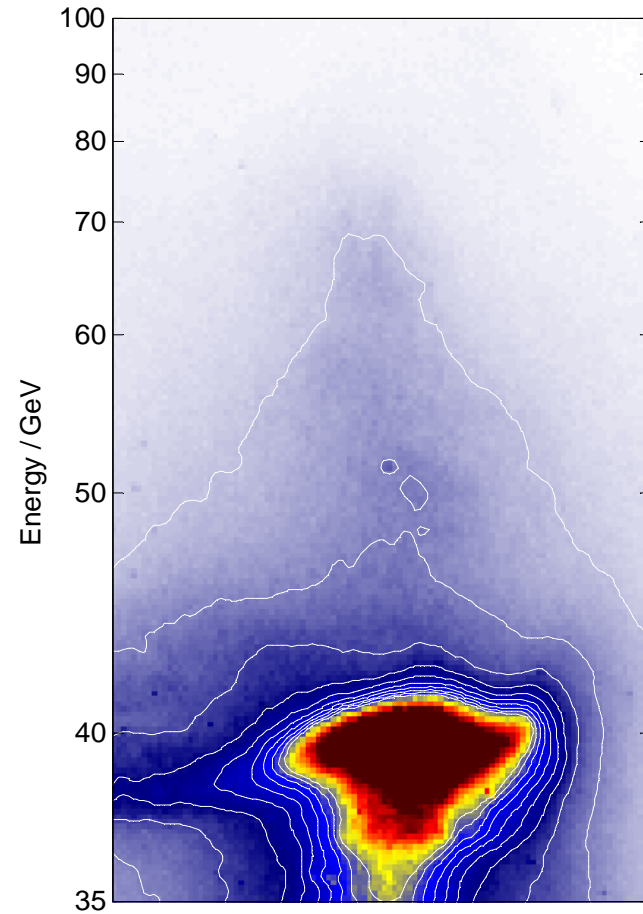
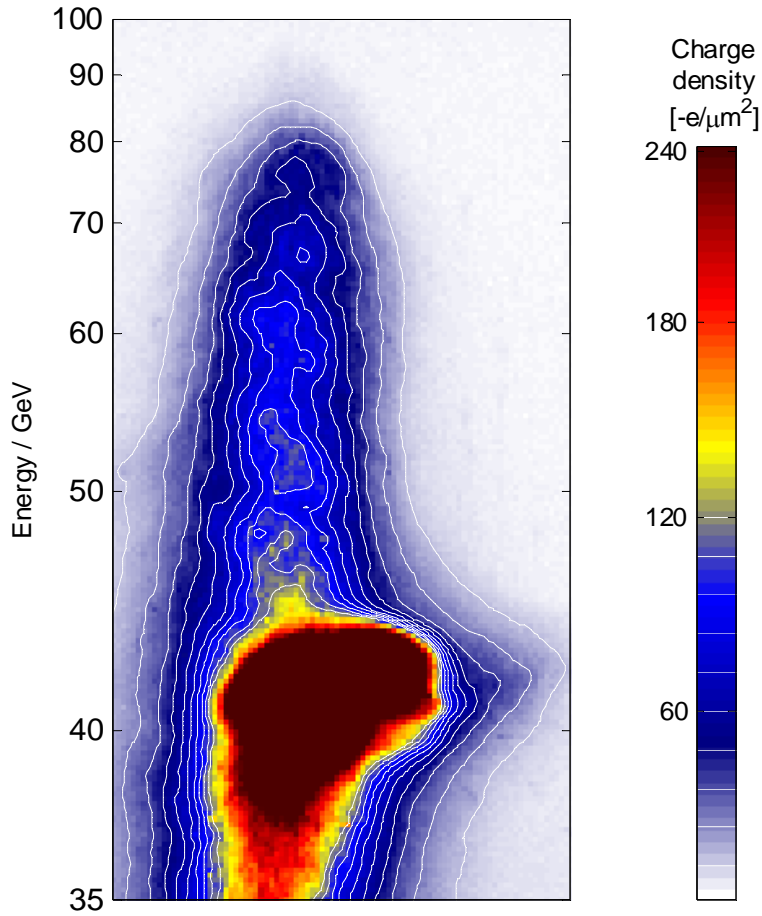
# What Determines the Maximum Energy?

- Plasma length
  - Oven length
  - Head erosion
- Hose instability
- Mobile ions
- Energy depletion of the drive beam (transformer ratio)



# 85 cm Plasma

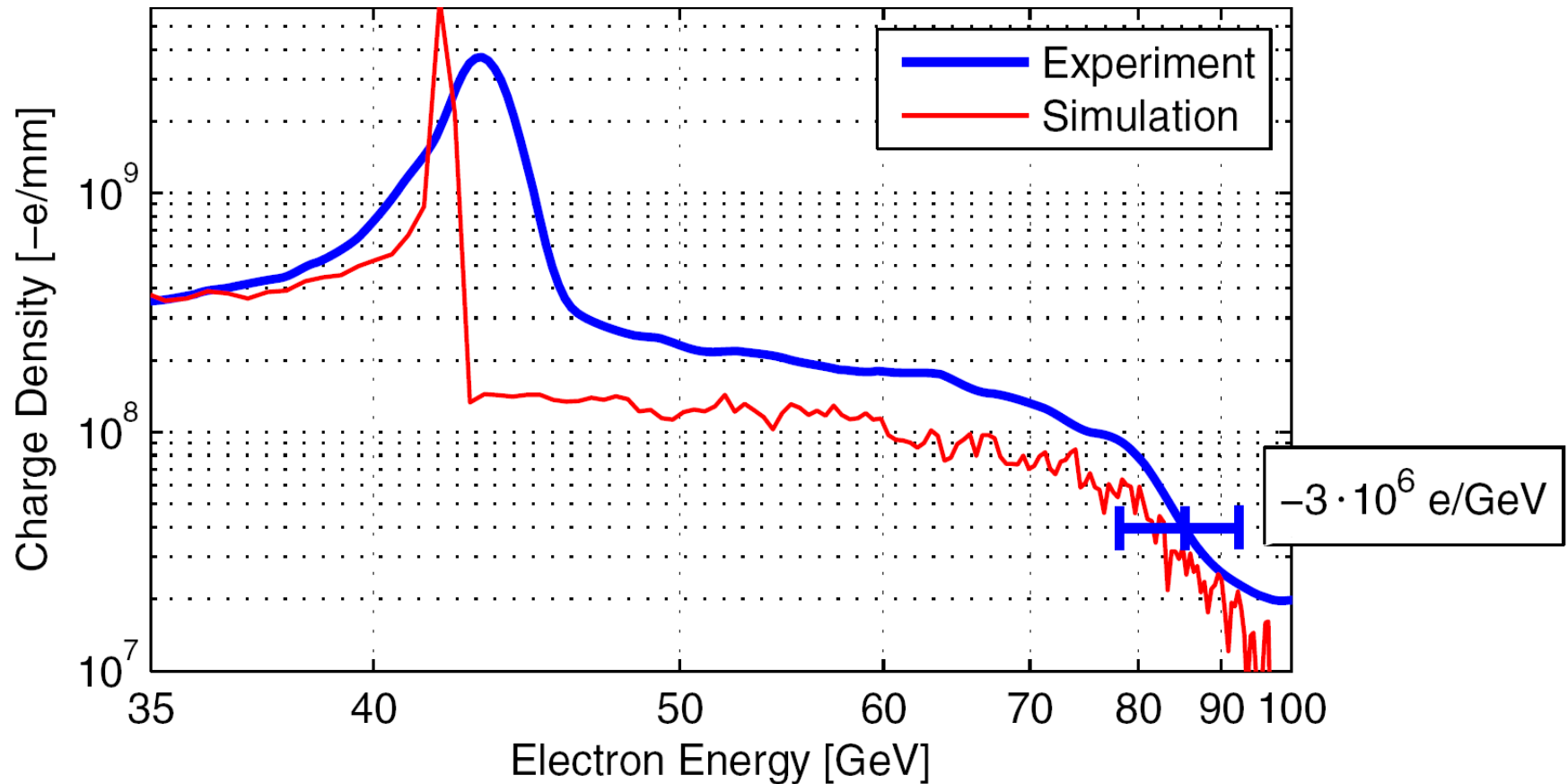
# 113 cm Plasma



# Simulations

- Match the phase space from LiTrack simulation to the measured energy spectrum before the plasma
- Use the corresponding longitudinal bunch profile
- Particle-In-Cell codes:
  - full PIC code: approximately 132,000 CPU hours for 85 cm plasma
  - QuickPIC: quasi-static approximation, 2760 CPU hours
- Simulation of
  - ⇒ field ionization
  - ⇒ motion of beam and plasma electrons
  - ⇒ wake formation
  - ⇒ acceleration
  - ⇒ energy spectrum

# Comparison to Simulations

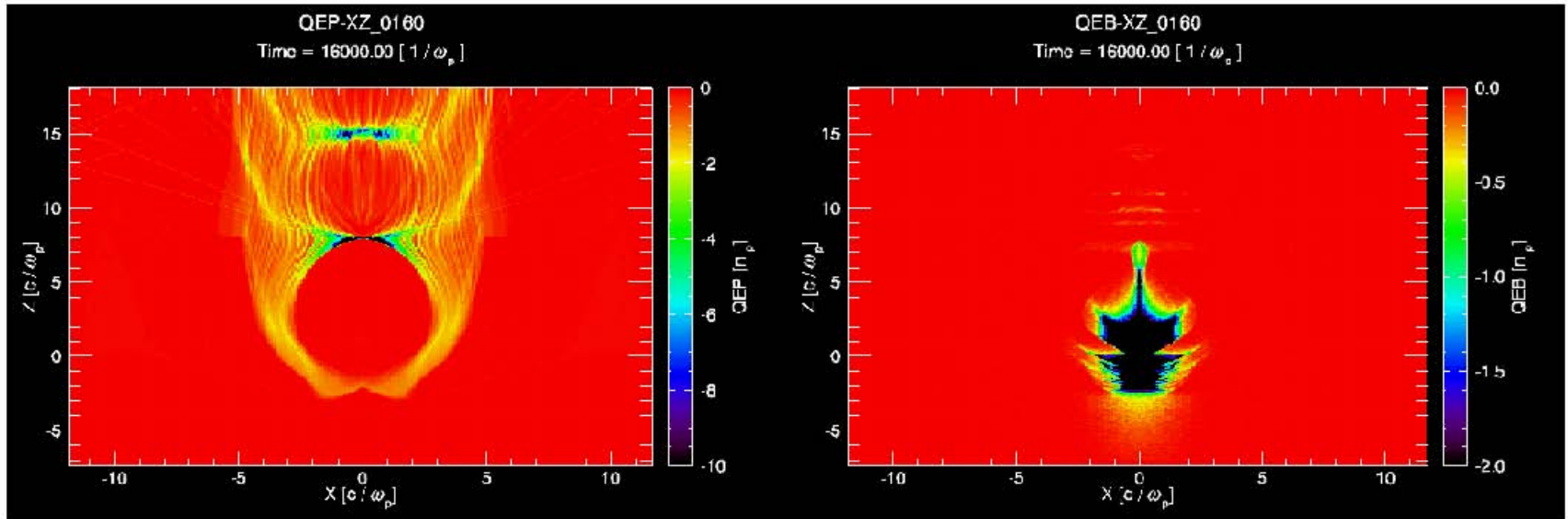


# Simulations

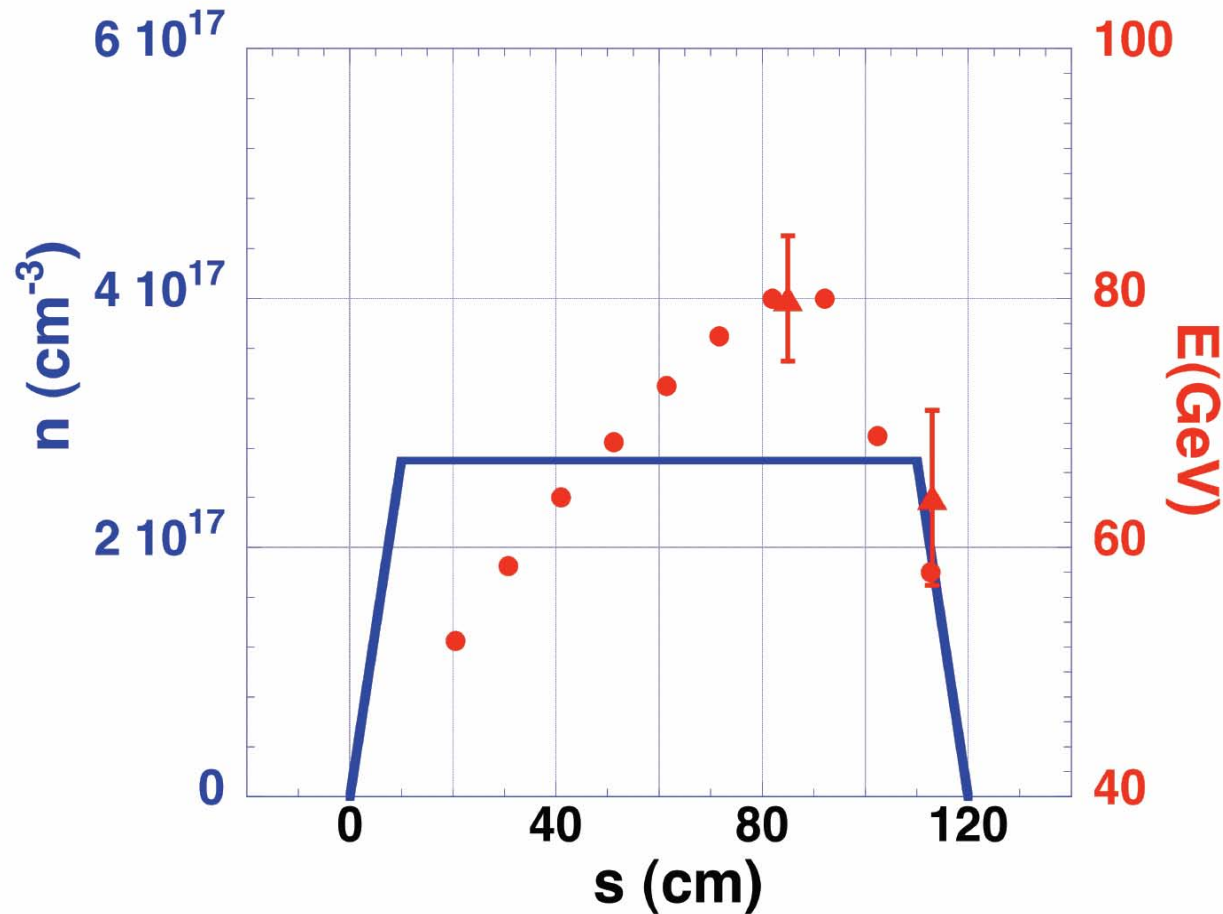
- Match the phase space from LiTrack simulation to the measured energy spectrum before the plasma
- Use the corresponding longitudinal profile and a measurement of the vapor density for QuickPIC:
  - ⇒ field ionization
  - ⇒ motion of beam and plasma electrons
  - ⇒ wake formation
  - ⇒ acceleration
  - ⇒ energy spectrum

# Simulations

- Determine head erosion as the reason for energy gain limitation

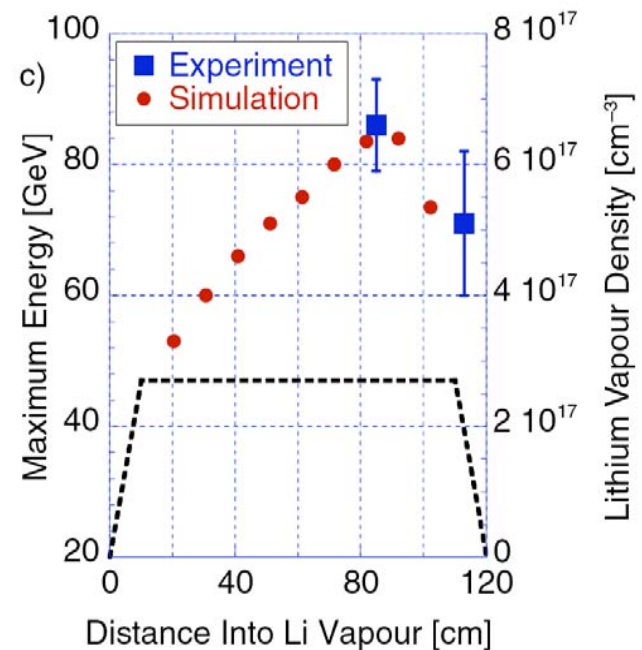
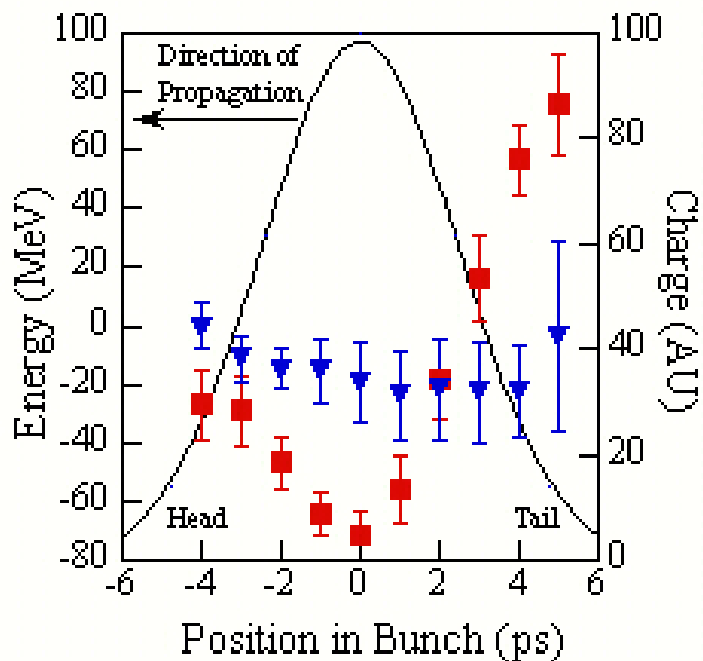


# Simulated Peak Energy

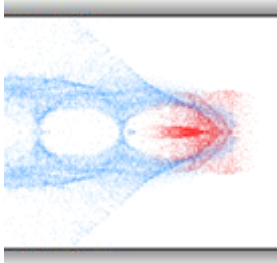


# Future Experiments at SABER

- Studies on self-injected particles
- Positron acceleration with short bunches
- Possibilities to overcome head erosion



# Energy Doubling of 42 GeV Electrons



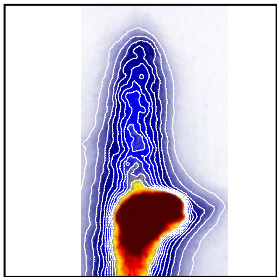
- **Plasma Wakefield Acceleration**

- Plasma Wakes
- What determines the maximum energy?
- Numerical Models



- **Experimental Setup**

- New plasma oven
- New spectrometer
- Higher energy in the drive beam



- **Results**

- Increased the energy from 42 to 80 GeV
- Head erosion limits energy gain at 85 cm in present setup
- Excellent agreement with simulations

# Presented by the E-167 Collaboration



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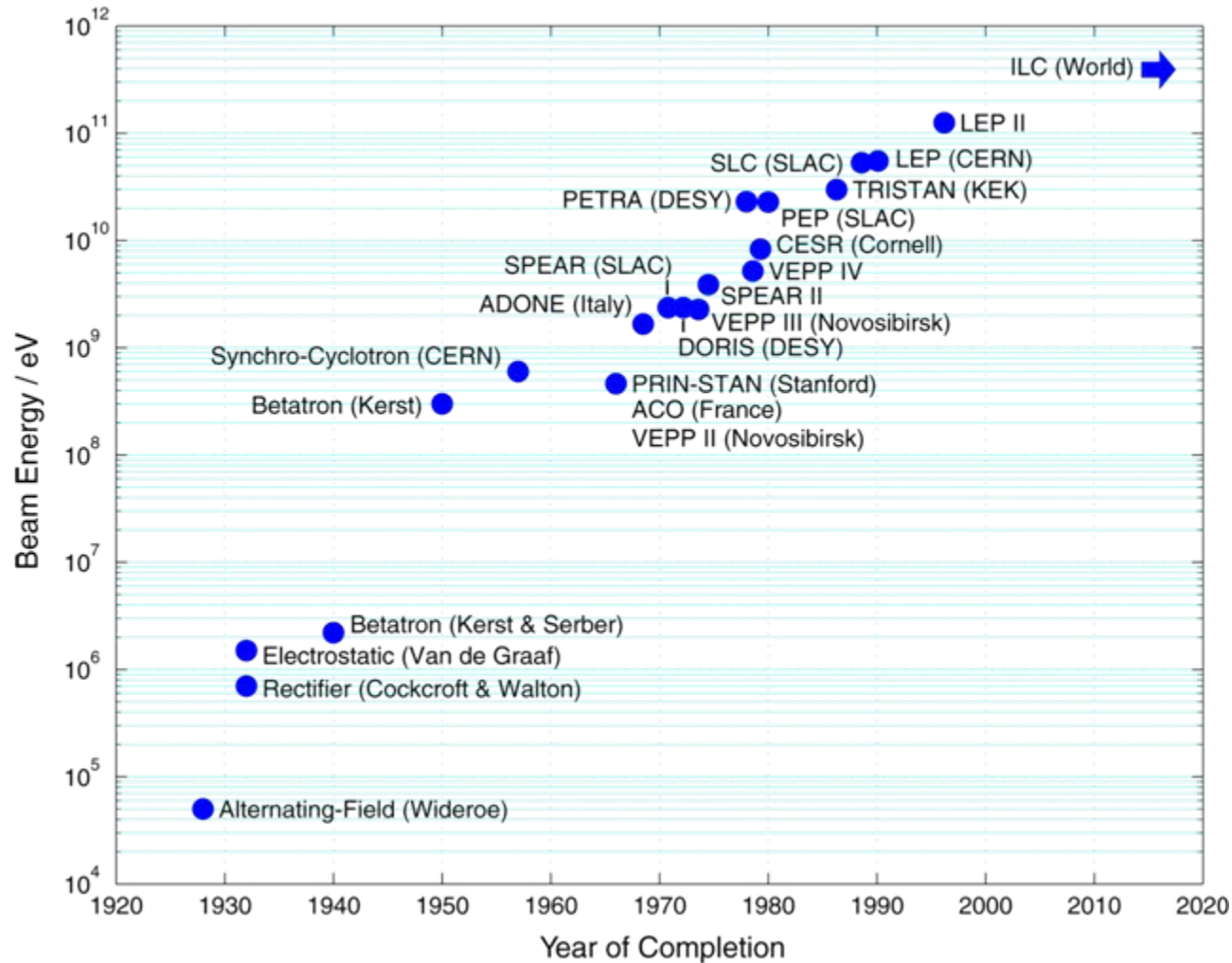


Work supported by Department of Energy contracts DE-AC02-76SF00515 (SLAC), DE-FG03-92ER40745, DE-FG03-98DP00211, DE-FG03-92ER40727, DE-AC-0376SF0098, and National Science Foundation grants No. ECS-9632735, DMS-9722121 and PHY-0078715.

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Please see: <http://www.slac.stanford.edu/~rasmus>

# Evolution of Electron Accelerators (Livingston Plot)



# An Unfair Comparison

