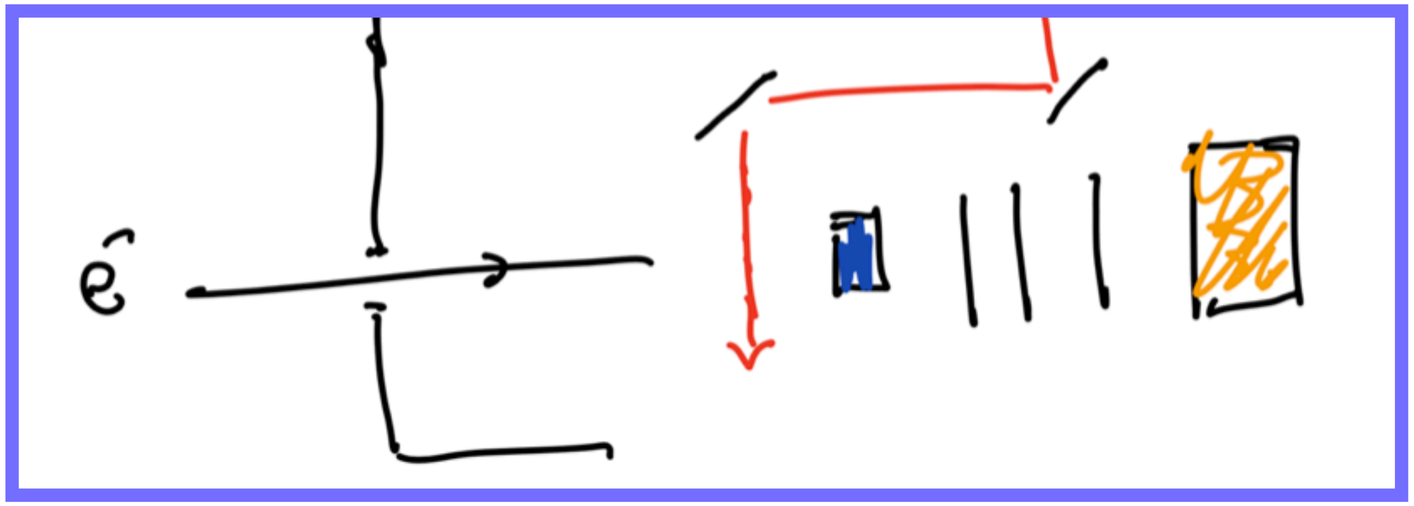
QED Beyond Schwinger Fields with ILC Fixed Target Beams



with Philip Bucksbaum,
David Reis, Sebastian Meuren

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ILCX
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There are still mysteries in QED, even at the MeV energy scale.

When electric fields become of the order of the “Schwinger field”

$$eE = m_e^2$$

they can spontaneously create e+e- pairs from the vacuum. What happens then ? Are there new effects from fields far above the Schwinger field strength ?

This question has its own intrinsic interest, but it is also relevant to other areas:

In “practical” units, the Schwinger field is

$$E_{cr} = 10^{18} \text{ V/m} \ , \ B_{cr} = 4 \times 10^{13} \text{ g}$$

Electric and magnetic fields of this magnitude are found in magnetars and active galactic nuclei. To model those system, we need to understand the physics of these high fields. Extreme pulsars are also accompanied by e+e- plasmas whose properties we would like to understand.

The development of advanced accelerators also depends on plasma codes with very high fields.

Beamstrahlung also involves the motion of electrons through extreme fields.   Proposals for very high energy e+e- colliders enter the quantum regime of beamstrahlung, where strong QED applies.

A new application comes in the study of γγ colliders. Canonically, a γγ collider uses high-energy γ’s produced by Compton scattering. We would like to understand how to model the interaction of the backscattered γ’s with the oncoming intense laser beam.

To perform modeling for all of these applications, we need plasma codes that accurately describe the QED strong field plasma regime.

Currently, this regime is modeled by particle-in-cell (PIC) codes that treat individual pair creation events as incoherent and ignore other possible quantum effects such as formation length ("local constant field approximation"). Ideally, we would like to have experimental data that smoothly interpolates between the weak-field and the QED plasma regime to stress-test existing codes and develop new strategies.

How do we obtain Schwinger fields in the laboratory?

Schwinger fields are of order $E_{cr}^2 = 10^{29}\ \mathrm{W/cm}^3$.

A focused PW laser can give $E^2 \sim 10^{23}\ \mathrm{W/cm}^3$

So, if we have an 1 GeV electron interacting with this laser in a head-on collision, the electron will feel Schwinger fields in its rest frame.

A figure of merit for strong QED experiments is

$$\chi = eE/m_e^2$$

To realize large χ, we would like to move up both in e-energy and in laser intensity.

In the 1990s, the SLAC experiment E-144 achieved

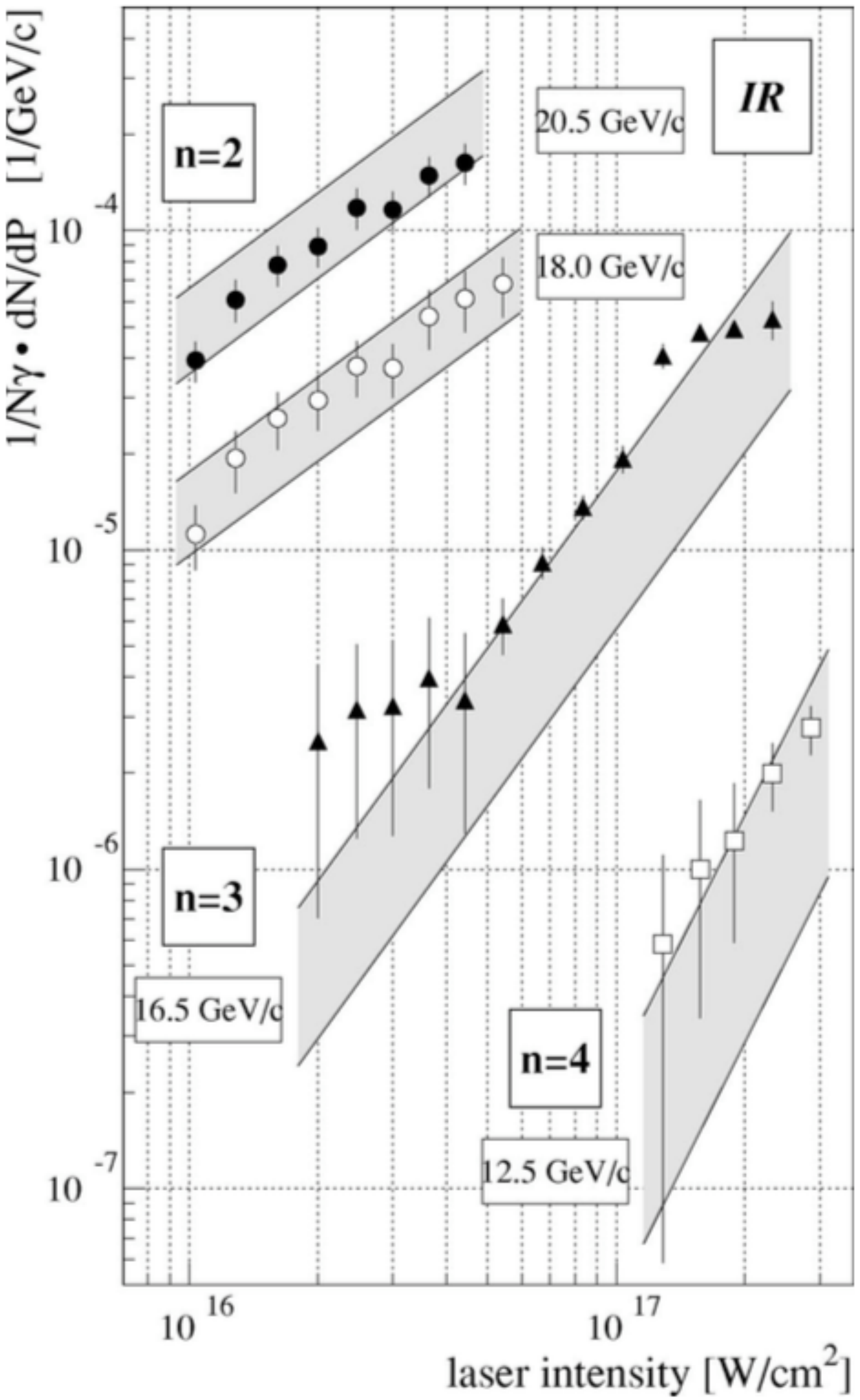
$$\chi \sim 0.3$$

using a 50 GeV e- beam and a 1 TW laser. They observed nonlinear Compton scattering,

$$e^- + n\gamma \to e^-\gamma$$

and multiphoton Breit-Wheeler production

$$e^- + n\gamma \to e^-e^+e^-$$



A second round of these experiments has now begun with E-320 at the FACET-II facility at SLAC (13 GeV x 20 TW).

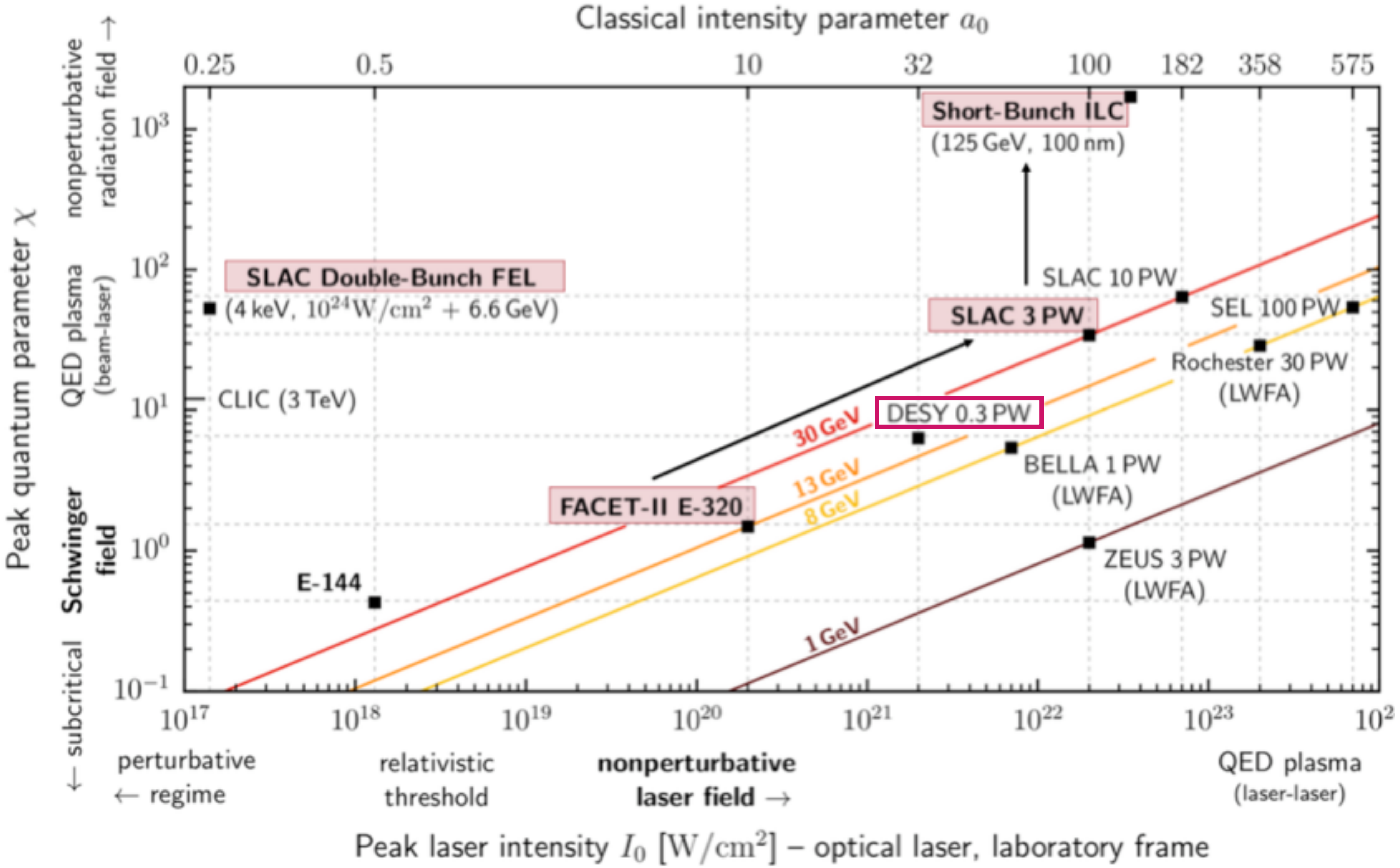
There is also a planned experiment at DESY, LUXE (16.5 GeV x 40 TW).

Both of these facilities will reach $\chi \sim 1$.

Upgrades are being discussed:

beam energy of 30 GeV at SLAC
a 350 TW laser at DESY

These will reach $\chi \sim 5 - 10$.


Classical intensity parameter a_0
0.25
0.5
10
32
100
182
358
575
Peak quantum parameter χ
nonperturbative radiation field ↑
QED plasma (beam-laser)
Schwinger field
↓ subcritical
10^3
10^2
10^1
10^0
10^{-1}
Short-Bunch ILC
(125 GeV, 100 nm)
SLAC Double-Bunch FEL
(4 keV, 10^{24}W/cm^2 + 6.6 GeV)
CLIC (3 TeV)
SLAC 10 PW
SEL 100 PW
SLAC 3 PW
Rochester 30 PW
(LWFA)
DESY 0.3 PW
30 GeV
13 GeV
8 GeV
1 GeV
BELLA 1 PW
(LWFA)
FACET-II E-320
ZEUS 3 PW
(LWFA)
E-144
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
10^{22}
10^{23}
10^2
perturbative
← regime
relativistic
threshold
nonperturbative
laser field →
QED plasma
(laser-laser)
Peak laser intensity I_0 [W/cm^2] – optical laser, laboratory frame

Meuren

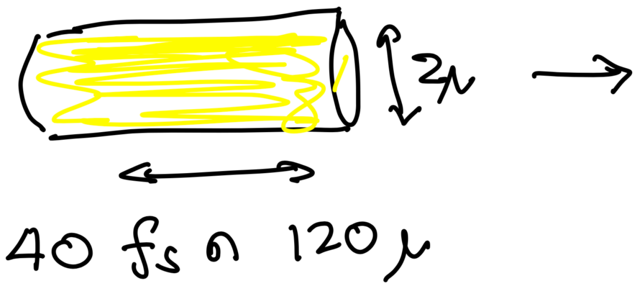
At the ILC, we will have the possibility of using a fixed-target e- beam of up to 125 GeV.

We anticipate that much more powerful lasers will be available at micron wavelengths (near IR). The main limitation for these lasers is not power but rather repetition rate.

A useful reference on the progress of high power lasers is: Dawson et al., HIgh Power Laser Science and Engineering, 7, e54 (2019).

For the mid-2030's, we expect a laser
with 10 PW bunches at 10/sec (or 100 PW at 1/sec)

and bunch shape:



giving $\sim 10^{24}\ \mathrm{W/cm^2}$. With a 120 GeV beam, this is nominally

$$\chi = 0.3 \frac{E_b}{10\ \mathrm{GeV}} \sqrt{\frac{2I}{10^{20}\mathrm{W/cm^2}}} \sim 250$$

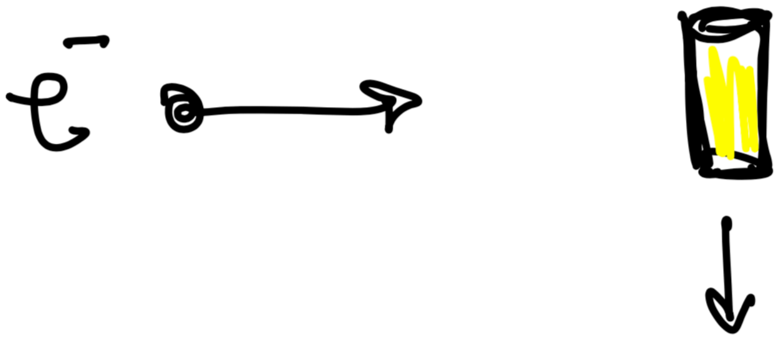
For an e- passing through such a laser beam, the radiation length is

$$\ell_{rad} = 0.7\mu \left(\frac{E}{10 \text{ GeV}} \right) \chi^{-2/3} = 0.3\mu$$

so an e- passing through this laser beam will almost always radiate, producing finally a small bunch of e- and e+ downstream.

We thus imagine several stages of an experimental program:

1. electron - laser bunch collisions at normal incidence



allowing the study of elementary e-γ interactions at

$$\chi \sim 100$$

The radiation length is ~ 1 μ in this geometry.

For a discussion of normal incidence experiments, see
Blackburn, Alderton, Marklund, Ridgers,
New J. Physics 21, 053040 (2019)

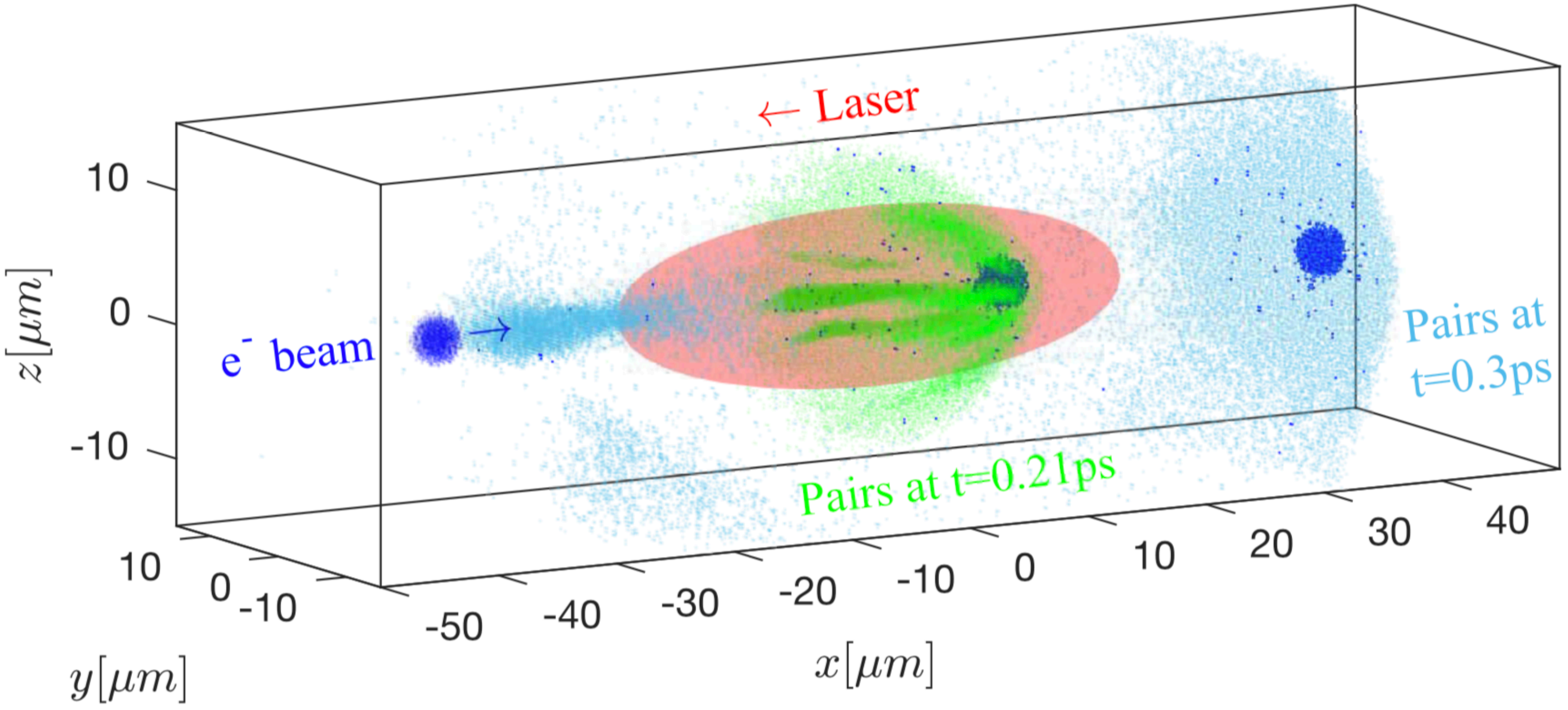
2. electron - laser bunch collisions head on

In this geometry, there are many stages of radiation, so the final output is an e+e- plasma. We have $\chi \sim 1000$ in the early stages of the cascade. For the final e+e- plasma, collective effects are important, and the plasma should be probed through its modes of excitation. The process of multiple pair creation is quantum coherent; does this affect the final plasma?

3. electron bunch - laser bunch collisions

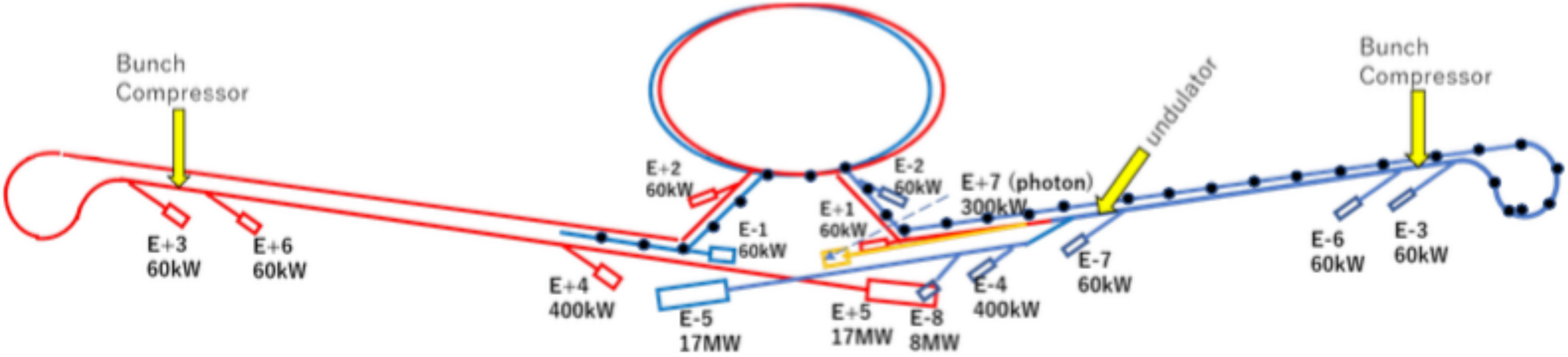
producing a high-density (incoherent) e+e- plasma of astrophysical interest

Qu, Meuren, and Fisch have simulated the production of this plasma and its dynamics (arXiv:2001.02590). We would like to know how close this simulation comes to the reality.

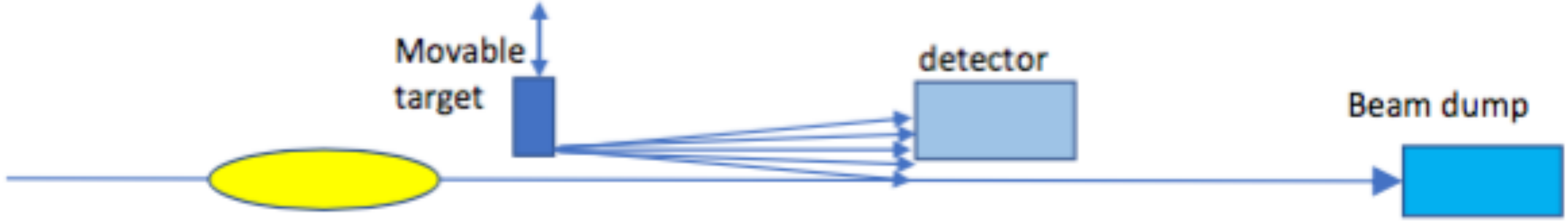


How can we realize this at the ILC ? (thanks to K. Yokoya)

We need a 120 GeV beam in a fixed target area. The location E-4 would be appropriate.



We would need the ability to put only a few electrons on target.

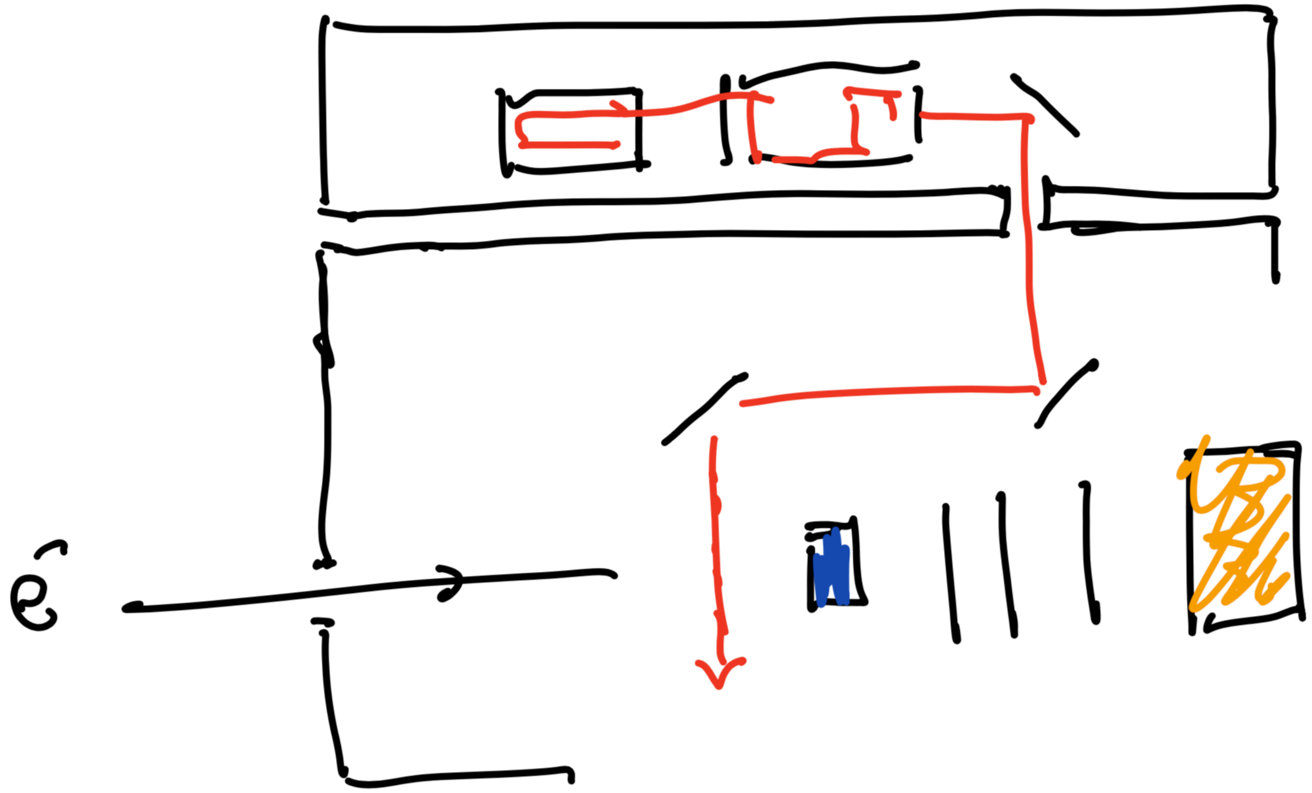


This capability is similar to that needed for an LDMX-type experiment. For the first phase, this experiment would need tracking and EM calorimetry similar to LDMX. Thus, these two experiments could share the space and facilities, though they could not run simultaneously.

For the later stages, we would need additional microwave sources and detectors, to probe modes of excitation of the e+e- plasma.

The placement of the laser is an issue.

First, the laser should ideally be underground near the experimental area. A high-power laser is room-size (10 m x 10 m) so it will need its own excavation.



High-power lasers are delicate and need to be adjusted daily. It should be possible to have frequent access to the laser room.

ILC will provide the world’s highest fixed-target electron beam. Pairing this beam with a high-power laser, we will be able to explore a new regime of QED at strong fields. Expect surprises !