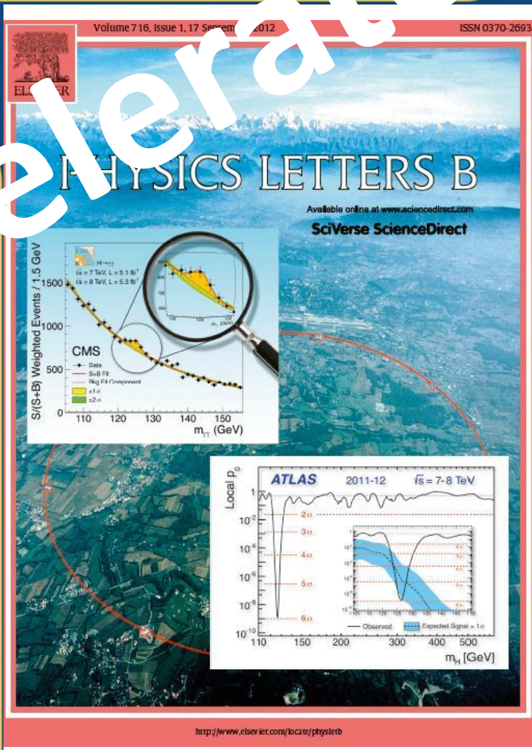
Plasma Wakefield Acceleration and the Future of Particle Physics

Symposium celebrating the 60th Birthday of
Halina Abramowicz
Tel Aviv University
January 5, 2014

Allen Caldwell
Max-Planck-Institut für Physik

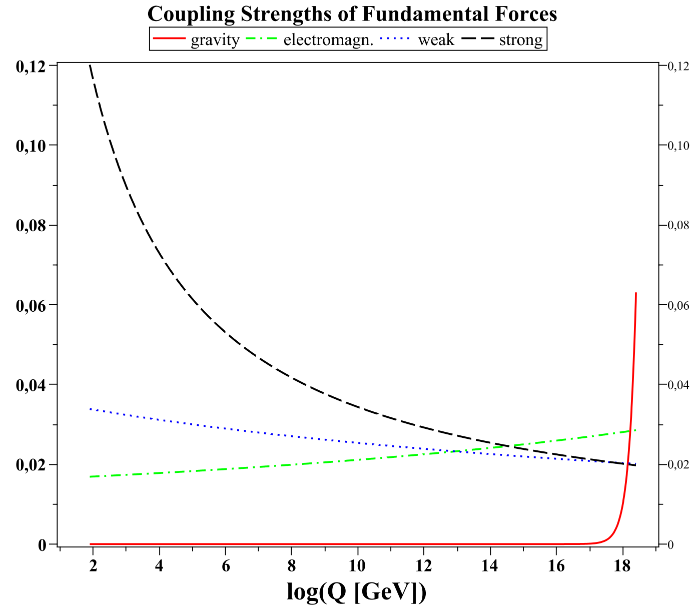


The most important tool for this development was the particle accelerator

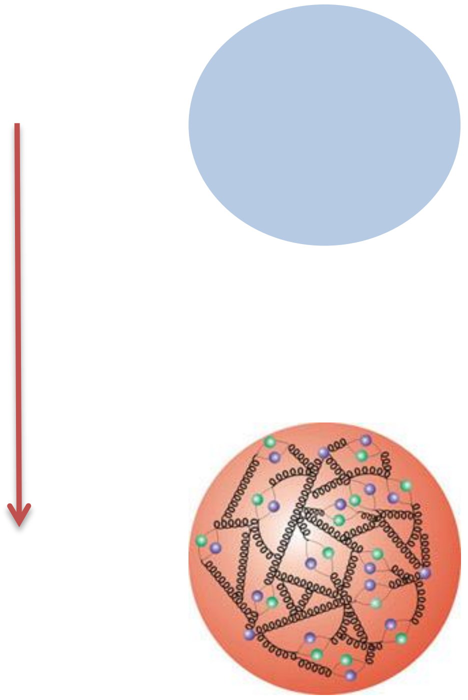
more discoveries to come

Many things not explained in the standard model:

- why three families
- matter/antimatter imbalance
- neutrinos and neutrino mass
- hierarchy problem/unification
- dark matter
- dark energy
- …
- other physics in principle in the Standard Model, but we lack the theoretical tools to understand them; e.g., confinement and the fundamental structure of hadrons



Increasing density

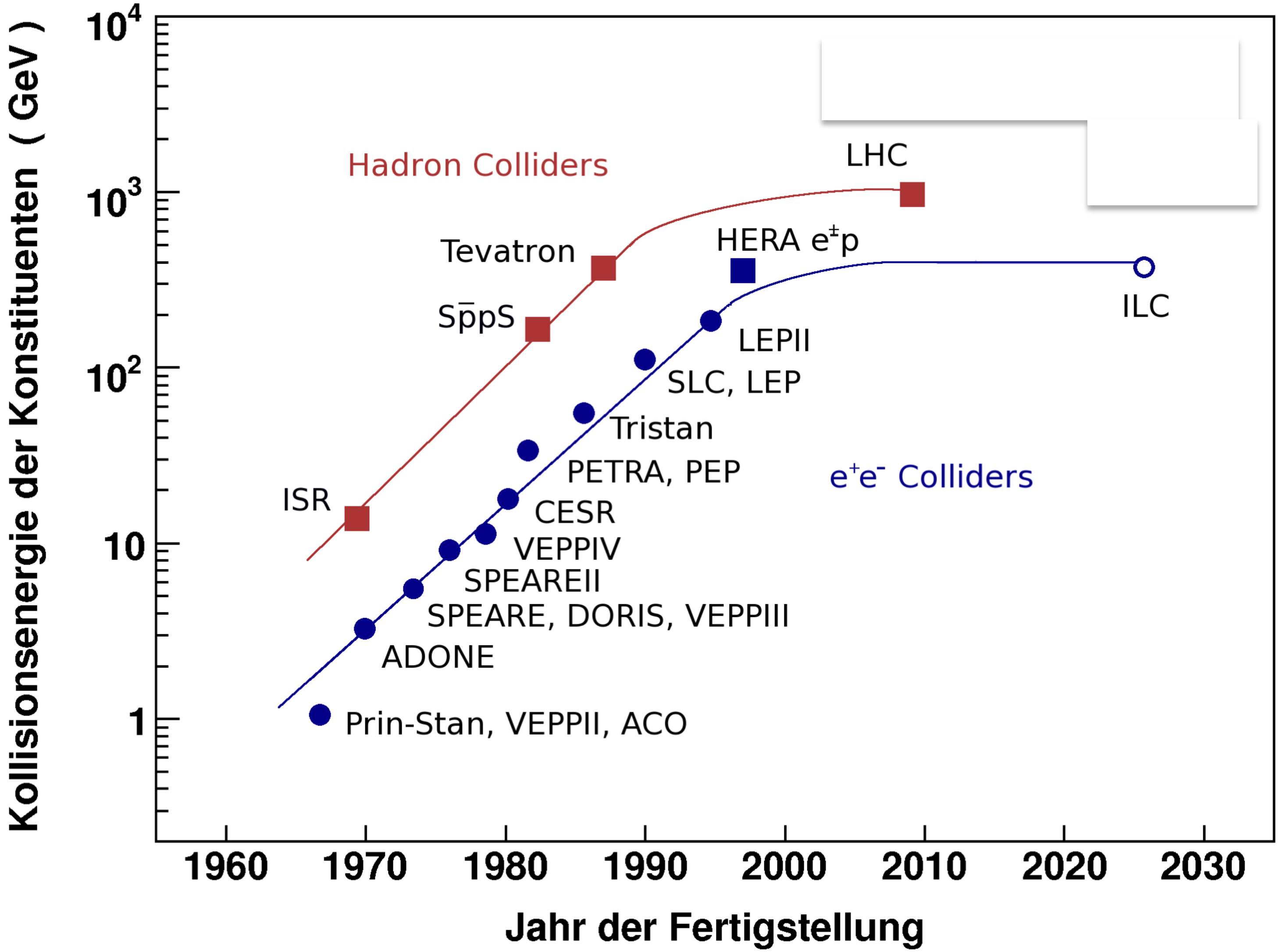


Low energy

High energy

Allen Caldwell

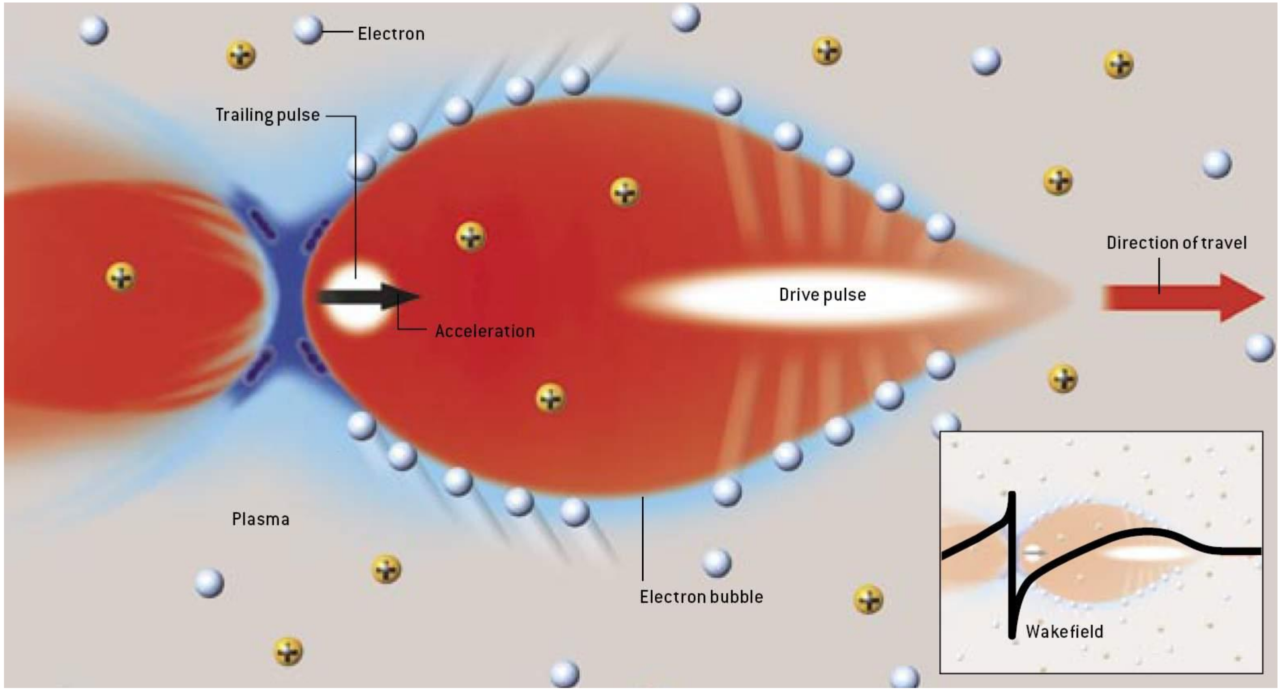
The Livingston plot shows a saturation …



Practical limit for accelerators at the energy frontier: Project size and cost increasing with the energy ! New technology needed…

Plasma Wakefield Acceleration

Original Proposal: T. Tajima and J. W. Dawson, *Phys. Rev. Lett.* **43** (1979) 267.



Nonlinear regime

Ch. Joshi, UCLA

Plasma frequency depends only on density:

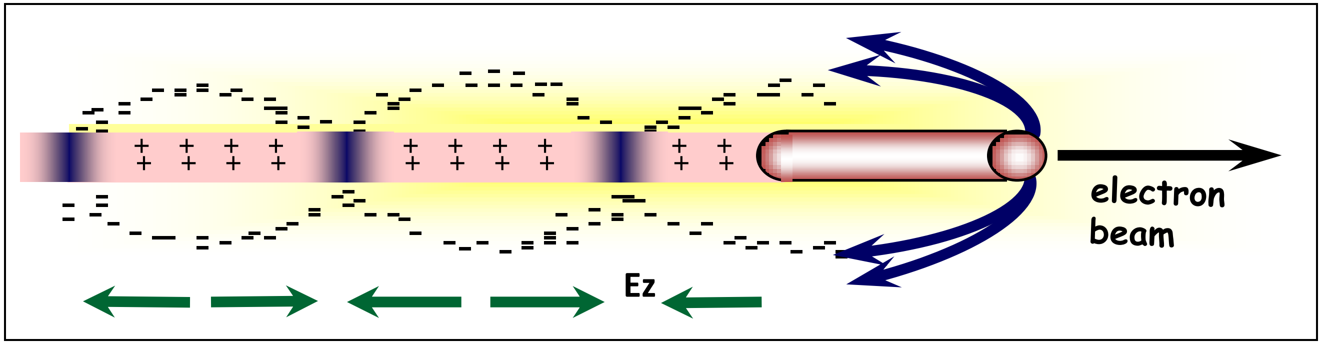
$$\omega_p^2 = \frac{4\pi n_p e^2}{m} \qquad k_p = \frac{\omega_p}{c} \qquad \lambda_p = \frac{2\pi}{k_p} = 1mm\sqrt{\frac{1 \cdot 10^{15}\ \mathrm{cm}^{-3}}{n_p}}$$

Produce an accelerator with mm (or less) scale ‘cavities’

Beam driven PWA

driving force: Space charge of drive beam displaces plasma electrons. → **Space charge oscillations (Harmonic oscillator)**

restoring force: Plasma ions exert restoring force



Electric fields can accelerate, decelerate, focus, defocus

Plasma also provides super-strong focusing force !
(many thousand T/m in frame of accelerated particles)

Proton-Driven Wakefield Acceleration

Both laser-driven and electron-bunch driven acceleration will require many stages to reach the TeV scale.

We know how to produce high energy protons (many TeV) in bunches with population > 10^{11}/bunch today, so if we can use protons to drive an electron bunch we could potentially have a simpler arrangement - single stage acceleration.

Linear regime ($n_b < n_0$):

$$E_{z,\max} \approx 2\ \mathrm{GeV/m} \cdot \left(\frac{N_b}{10^{10}}\right) \cdot \left(\frac{100\ \mu\mathrm{m}}{\sigma_z}\right)^2$$

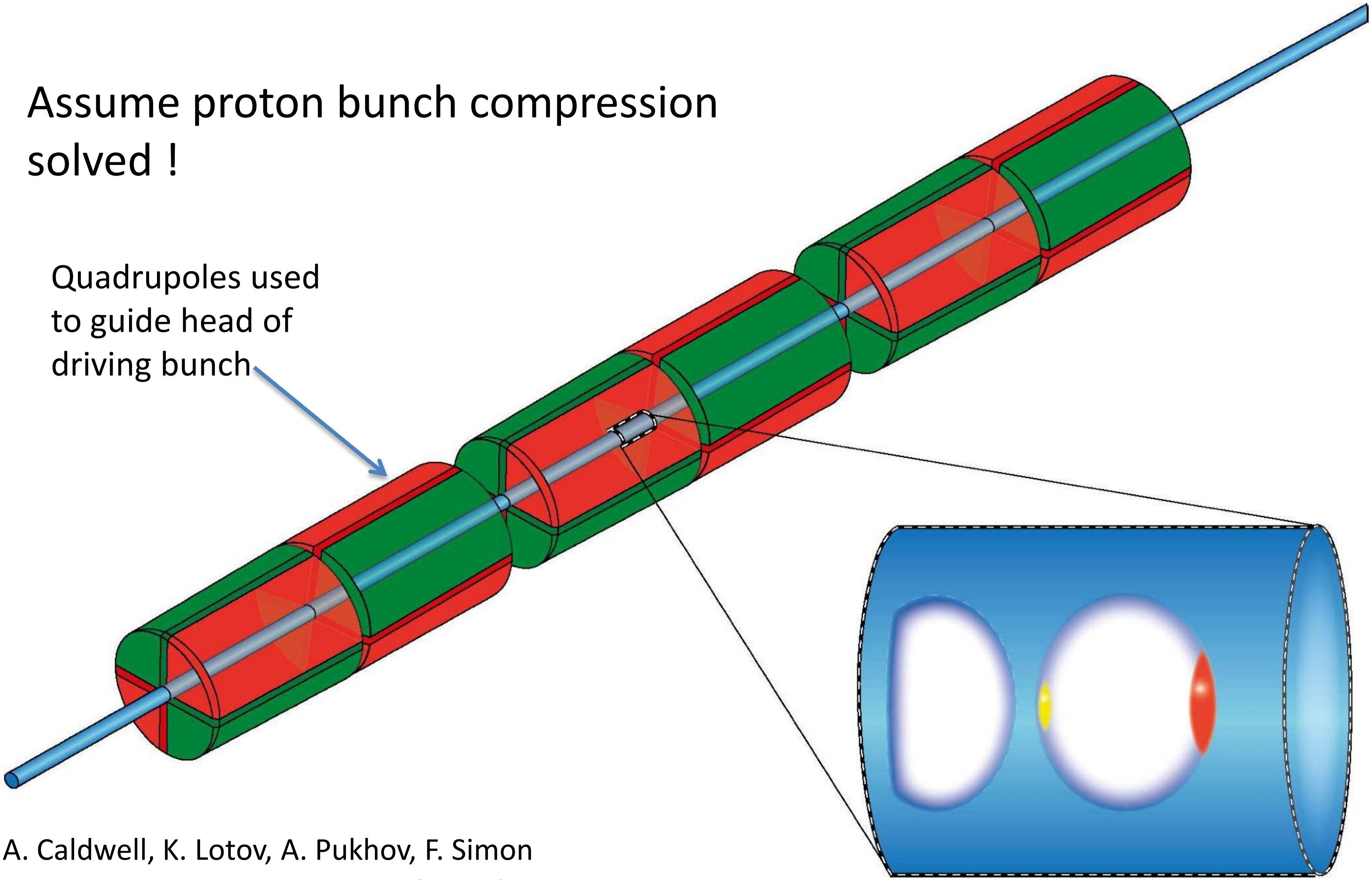
Need very short proton bunches for strong gradients. Today's proton beams have

$$\sigma_z \approx 10 - 30\ \mathrm{cm}$$

Simulation study

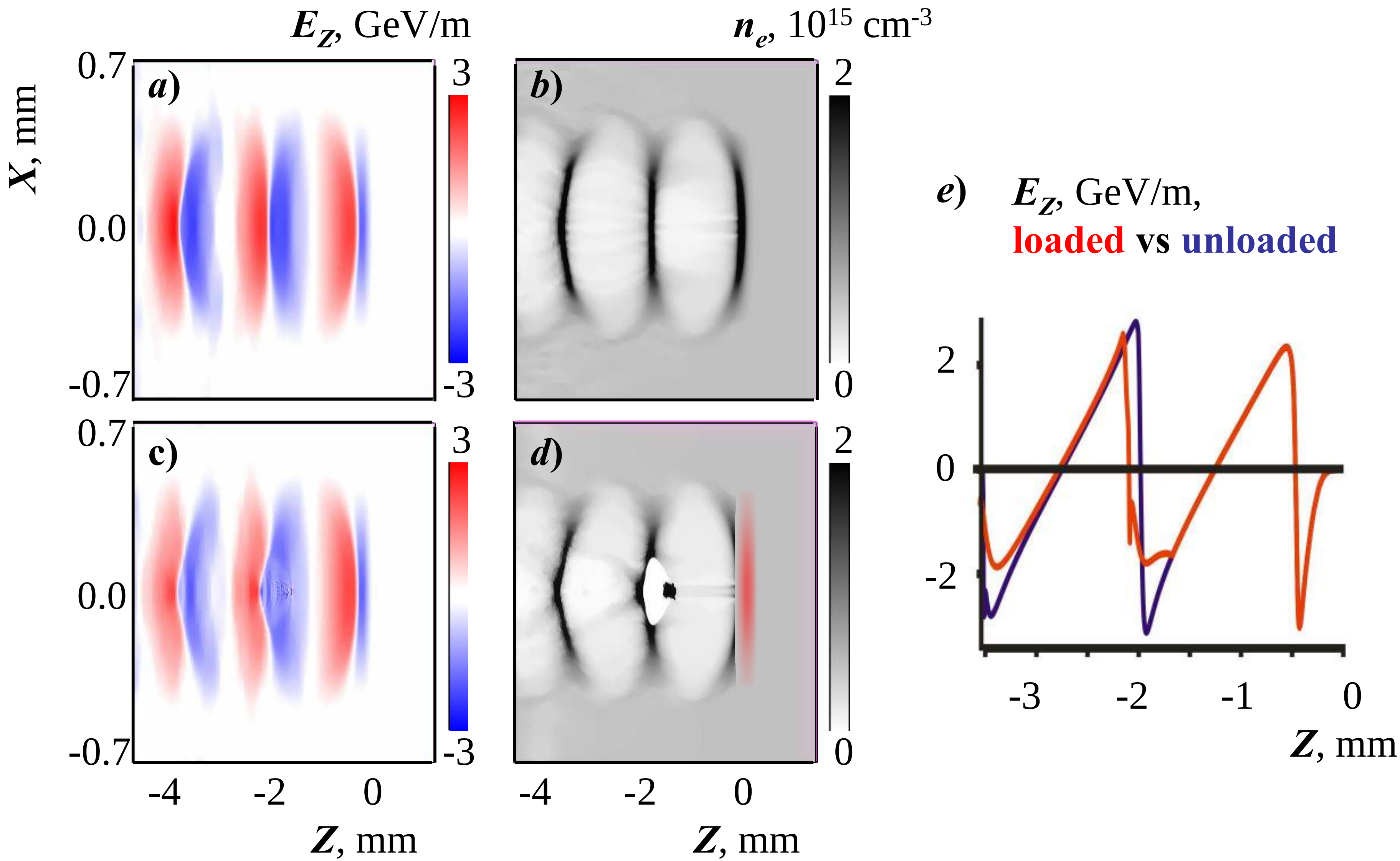
Assume proton bunch compression solved !

Quadrupoles used to guide head of driving bunch



A. Caldwell, K. Lotov, A. Pukhov, F. Simon
Nature Physics ***5, 363 - 367 (2009)***

Densities & Fields

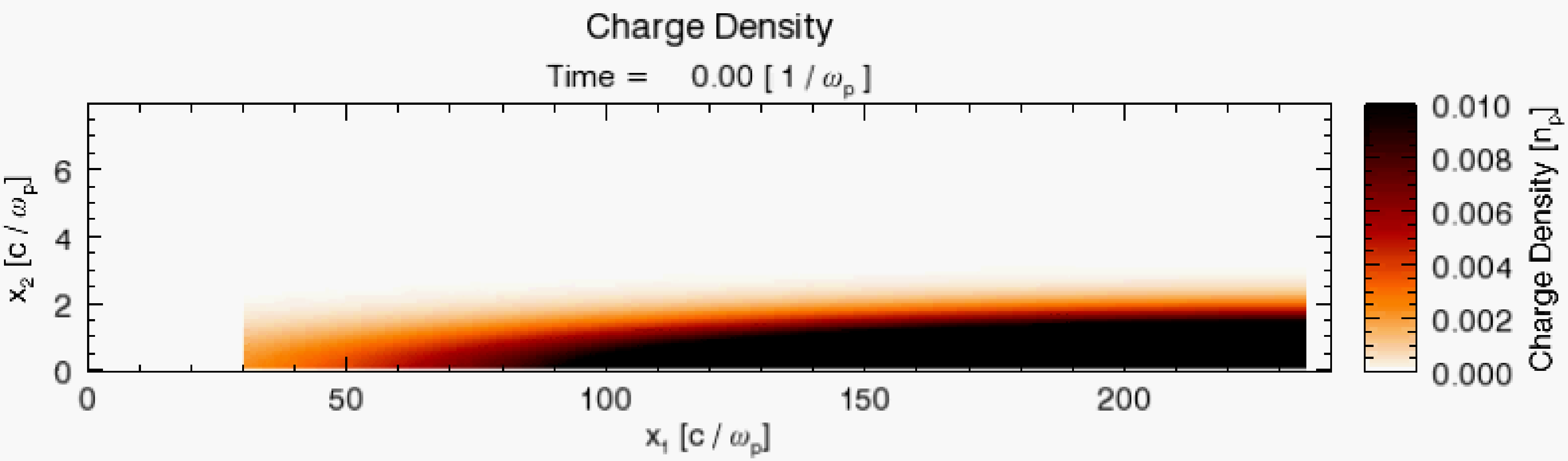


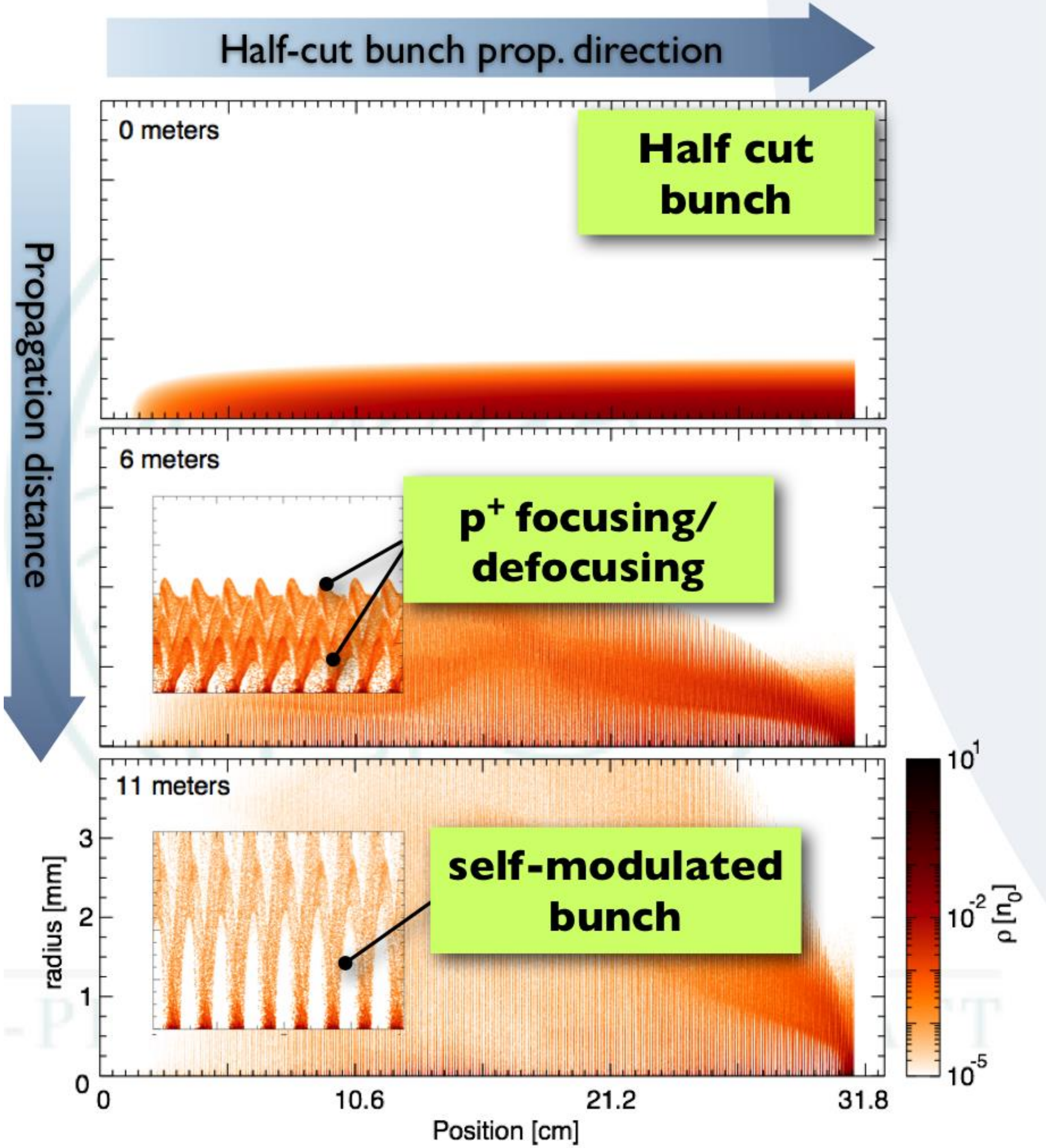
PWA via Modulated Proton Beam

Producing short proton bunches not possible today w/o major investment. Not an option for the short term …

Instead, we investigated modulating a long bunch to produce a series of 'micro'-bunches in a plasma.

The microbunches are generated by a transverse modulation of the bunch density (transverse two-stream instability). The microbunches are naturally spaced at the plasma wavelength, and act constructively to generate a strong plasma wake. Investigated both numerically and theoretically (N. Kumar, A. Pukhov, and K. V. Lotov, Phys. Rev. Lett. **104**, 255003 (2010)).


Charge Density
Time = 0.00 [1 / ωp]
x2 [c / ωp]
6
4
2
0
0
50
100
150
200
x1 [c / ωp]
0.010
0.008
0.006
0.004
0.002
0.000
Charge Density [np]



Fields > GV/m also possible with modulated long beam !

Phase velocity of the wake

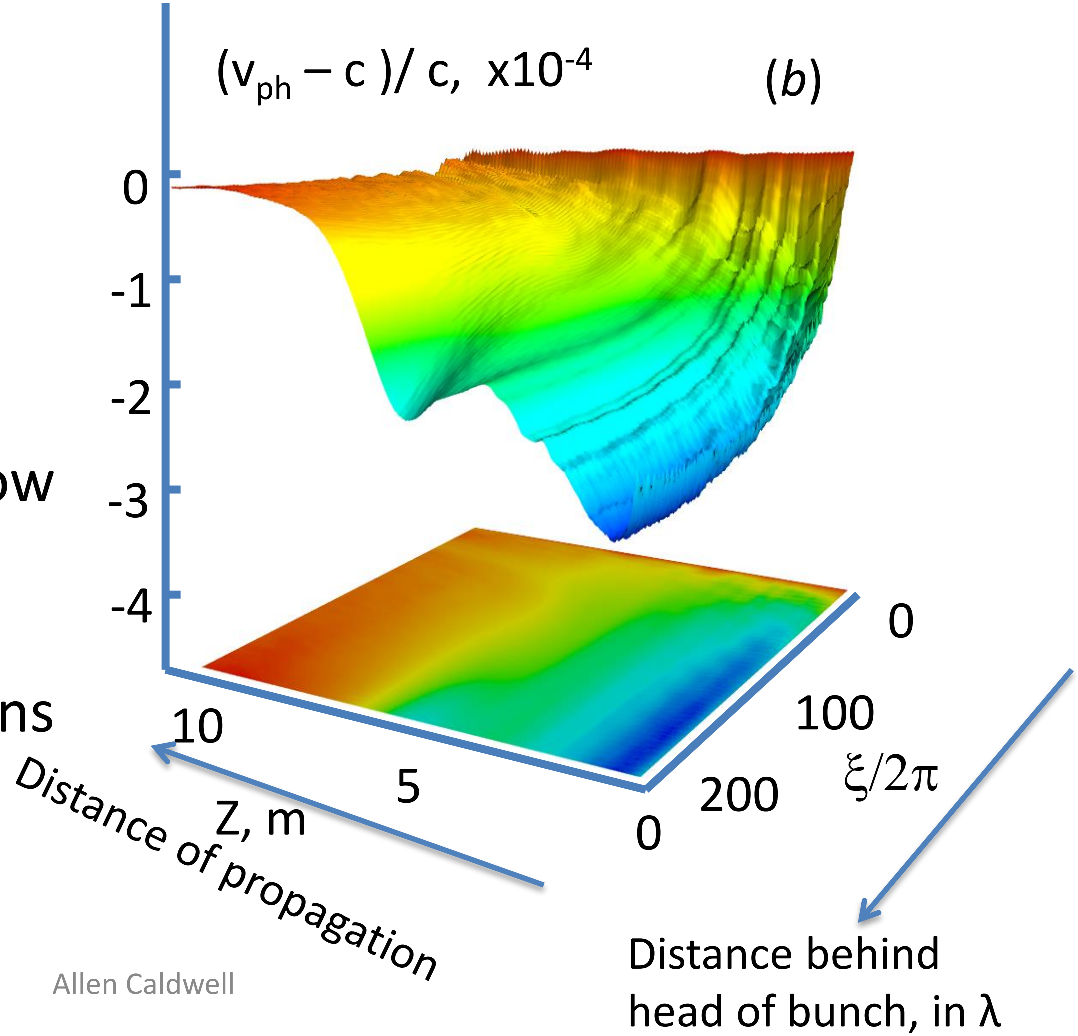
To trap & accelerate electrons in the wake of the protons, it is important that the wake phase velocity matches the electron velocity. Initially, the gamma-factor is

$\gamma_{min} \sim 40$

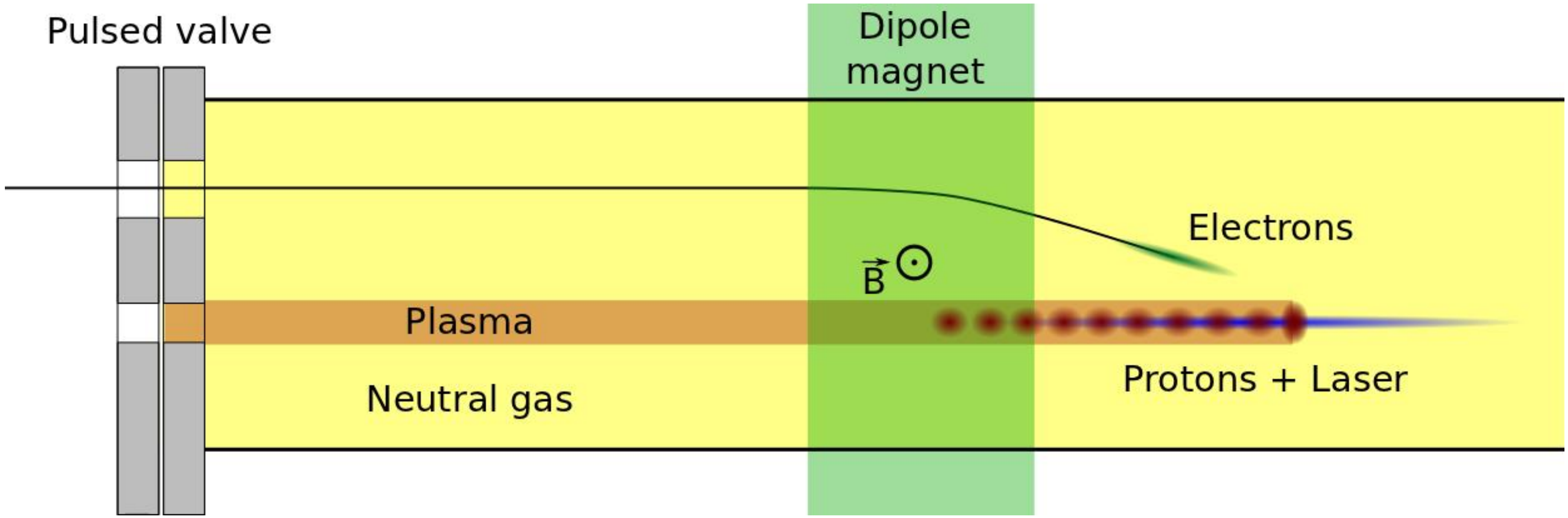
This is order of magnitude below that of the beam.

Requires that we inject electrons after the phase velocity has stabilized.

Pukhov et al., Phys Rev Lett (2011)



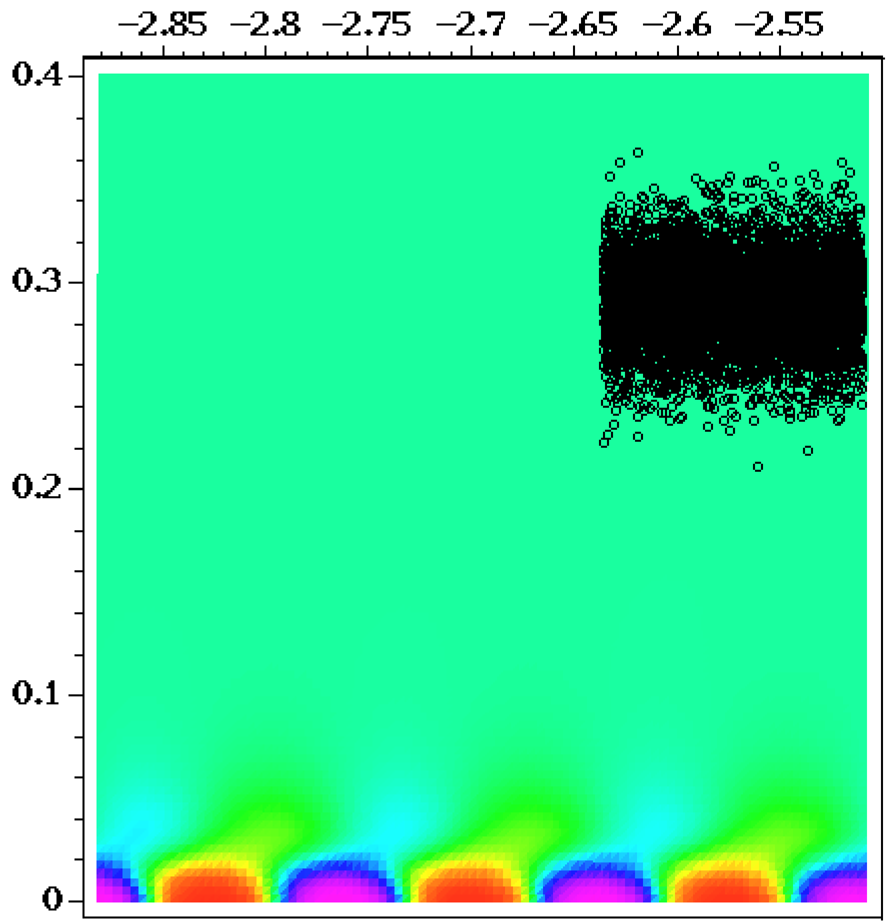
Solution: Delayed Electron Injection



Electron bunch injected off-axis at an angle, so that it merges with the proton bunch once the modulation is developed and the phase velocity is high.

Electron injection needs to occur after modulation has completed. For single plasma cell experiment, we achieve this using side-injection.

Simulations indicate can capture up to 40% of electron bunch this way.



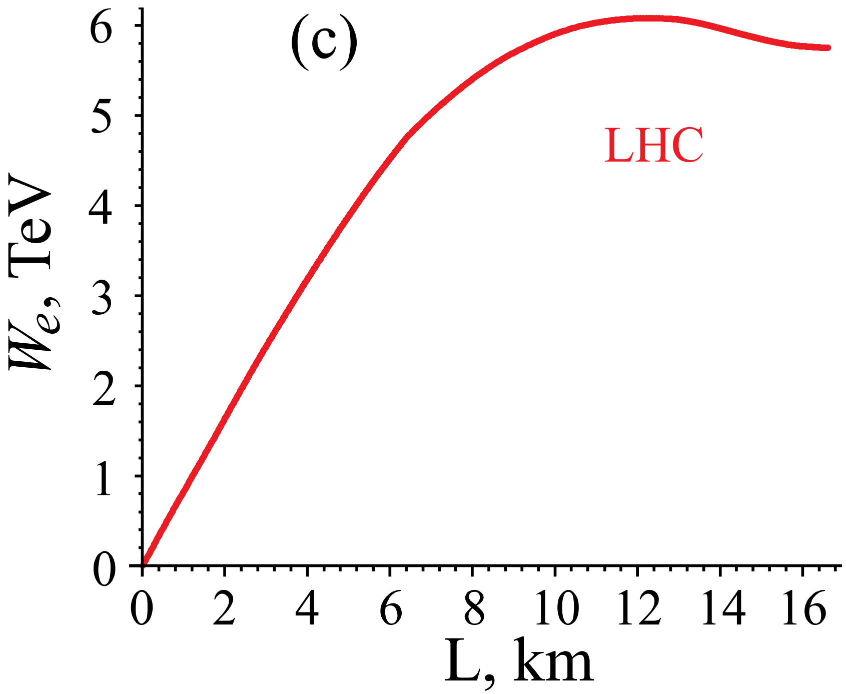
Outlook

Long term prospects for modulated proton bunch intriguing:

simulation of existing LHC bunch in plasma with trailing electrons …

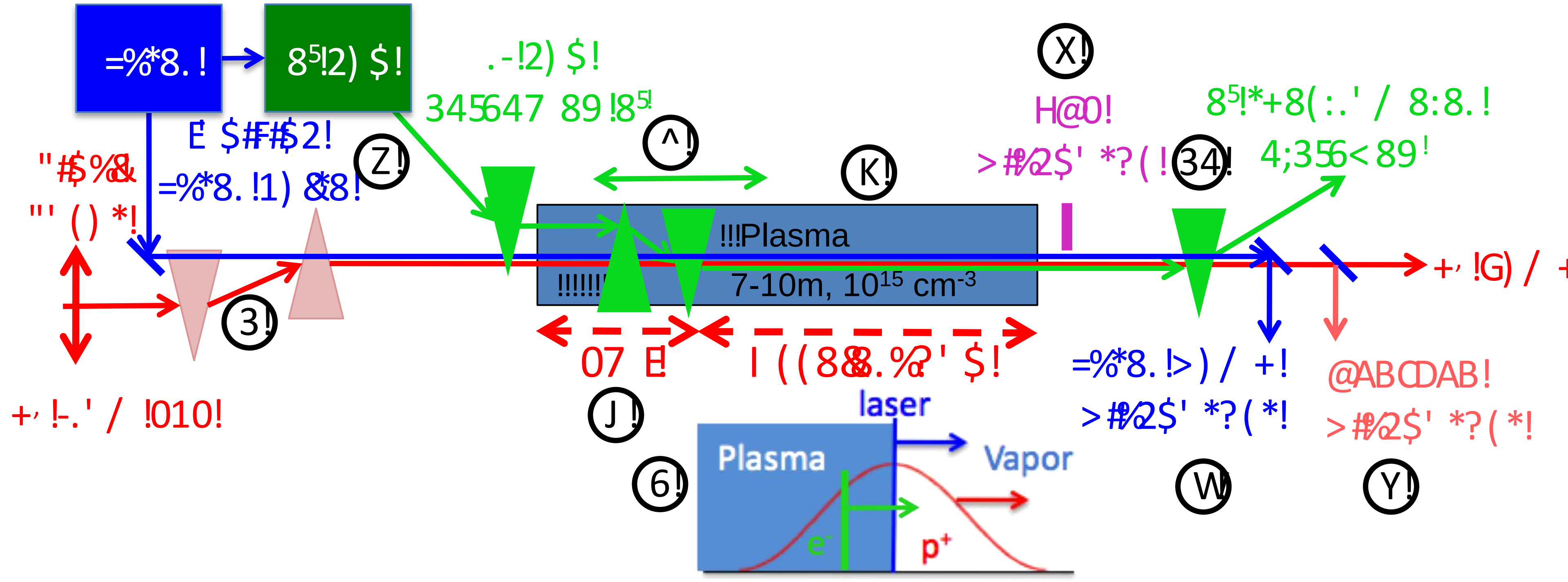
A. Caldwell, K. V. Lotov, Phys. Plasmas **18**, 13101 (2011)

Electron energy gain



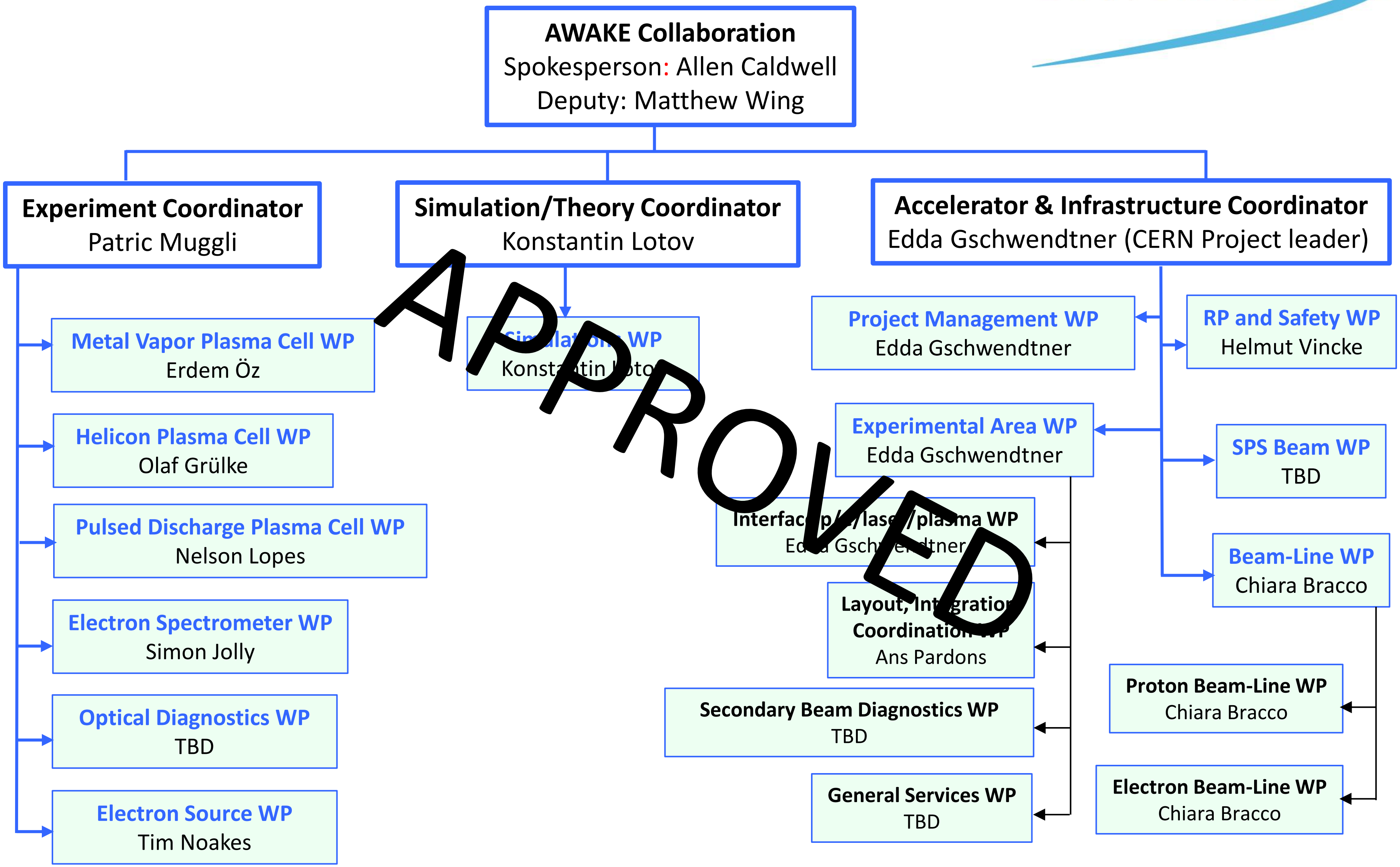
Miracle: no guiding magnetic fields necessary !

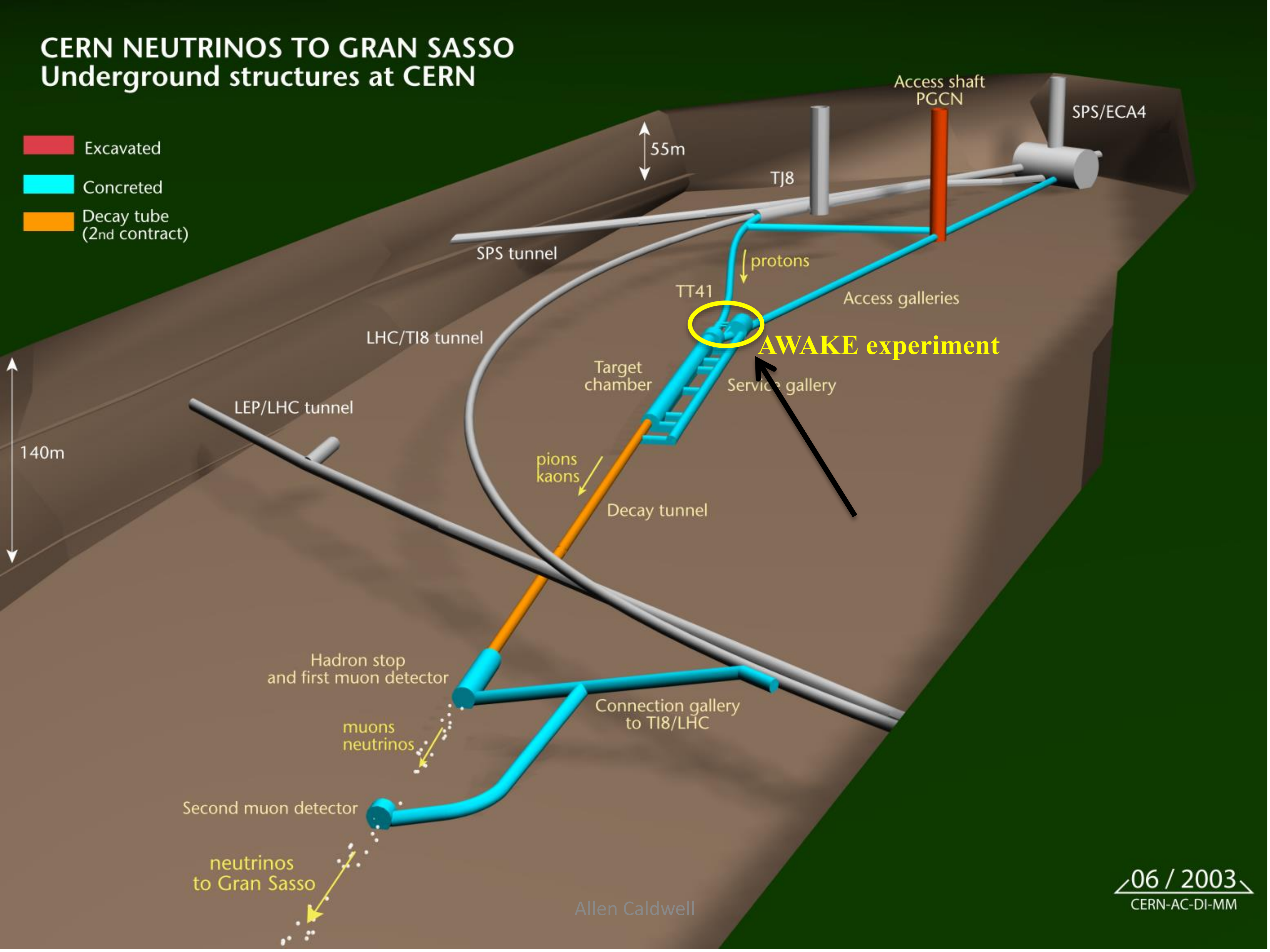
But – luminosity will be big issue !

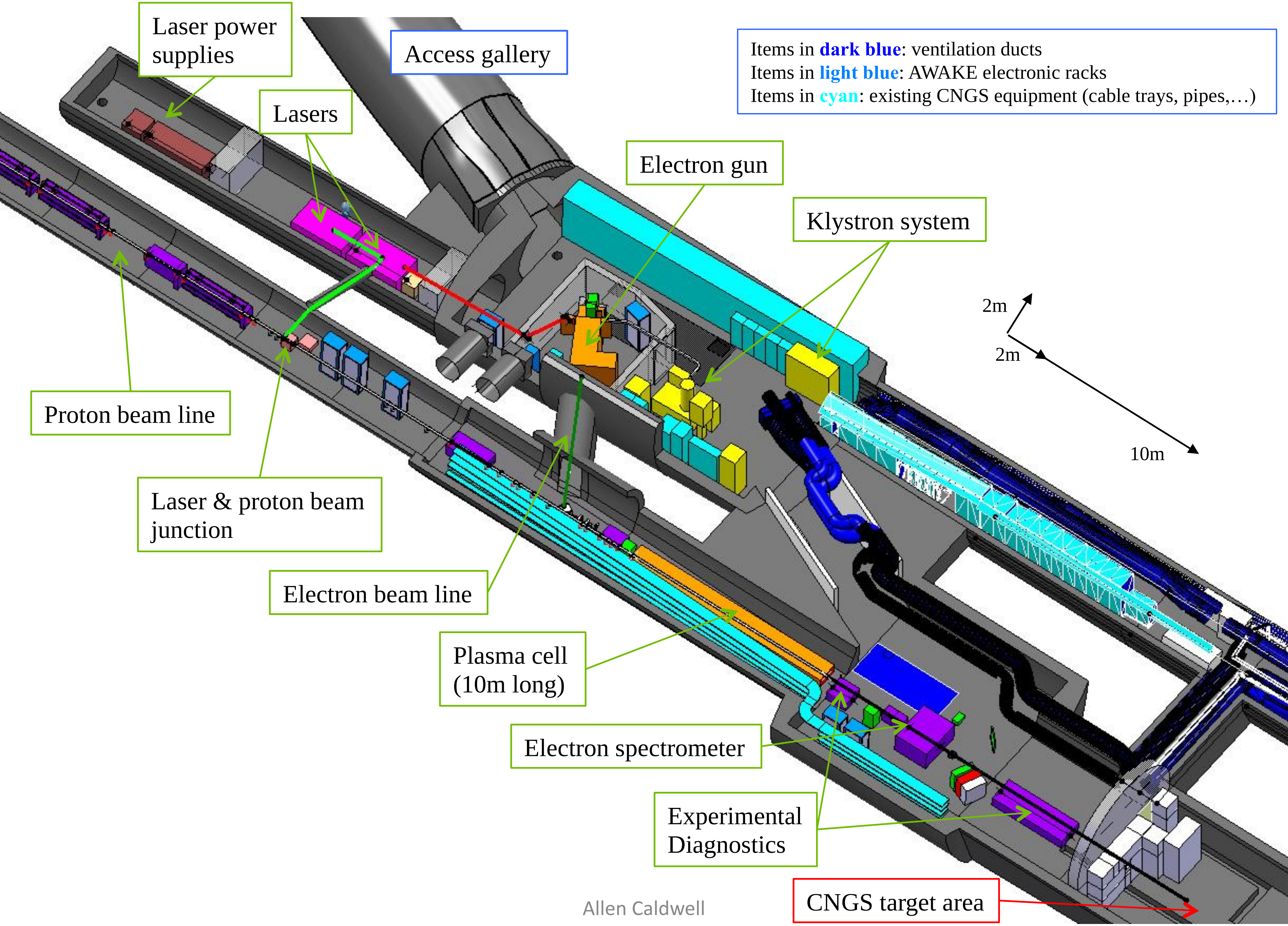


1. Merging of SPS proton beam & ionizing/seeding laser pulse
2. Schematic relative timing
3. SMI developing, electron bunch parallel to proton bunch
4. Acceleration sections
5. Laser pulse dumped & diagnosed
6. Electro-optical sampling diagnostic
7. Transition radiation diagnostics
8. RF electron gun
9. e/p bunch merging section
10. Electron spectrometer system

Project Structure

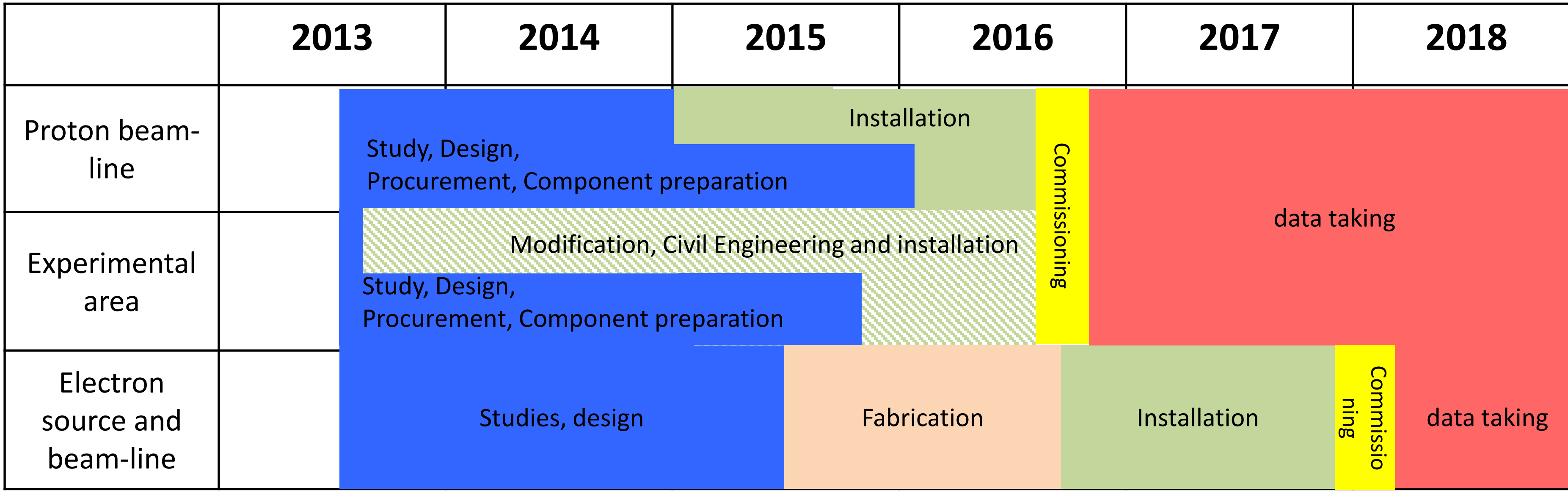



CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN
Excavated
Concreted
Decay tube
(2nd contract)
55m
140m
TJ8
Access shaft
PGCN
SPS/ECA4
SPS tunnel
protons
TT41
Access galleries
AWAKE experiment
LHC/TI8 tunnel
Target
chamber
Service gallery
LEP/LHC tunnel
pions
kaons
Decay tunnel
Hadron stop
and first muon detector
Connection gallery
to TI8/LHC
muons
neutrinos
Second muon detector
neutrinos
to Gran Sasso
06 / 2003
CERN-AC-DI-MM



Laser power supplies
Access gallery
Items in dark blue: ventilation ducts
Items in light blue: AWAKE electronic racks
Items in cyan: existing CNGS equipment (cable trays, pipes,…)
Lasers
Electron gun
Klystron system
2m
2m
10m
Proton beam line
Laser & proton beam junction
Electron beam line
Plasma cell (10m long)
Electron spectrometer
Experimental Diagnostics
CNGS target area

Time-scale for AWAKE



Science Program (first three years after start of data taking):

1. Benchmark experiments – first ever proton-driven plasma wakefields
2. Detailed comparison of experimental measurements with simulations
3. Demonstration of high-gradient acceleration of electrons
4. Develop long, scalable & uniform plasma cells; test in AWAKE experiment
5. Develop scheme for production and acceleration of short proton bunches

Goal: Design high quality & high energy electron accelerator based on acquired knowledge.

A possible future

electron-positron collider based on proton driven plasma wakefield acceleration

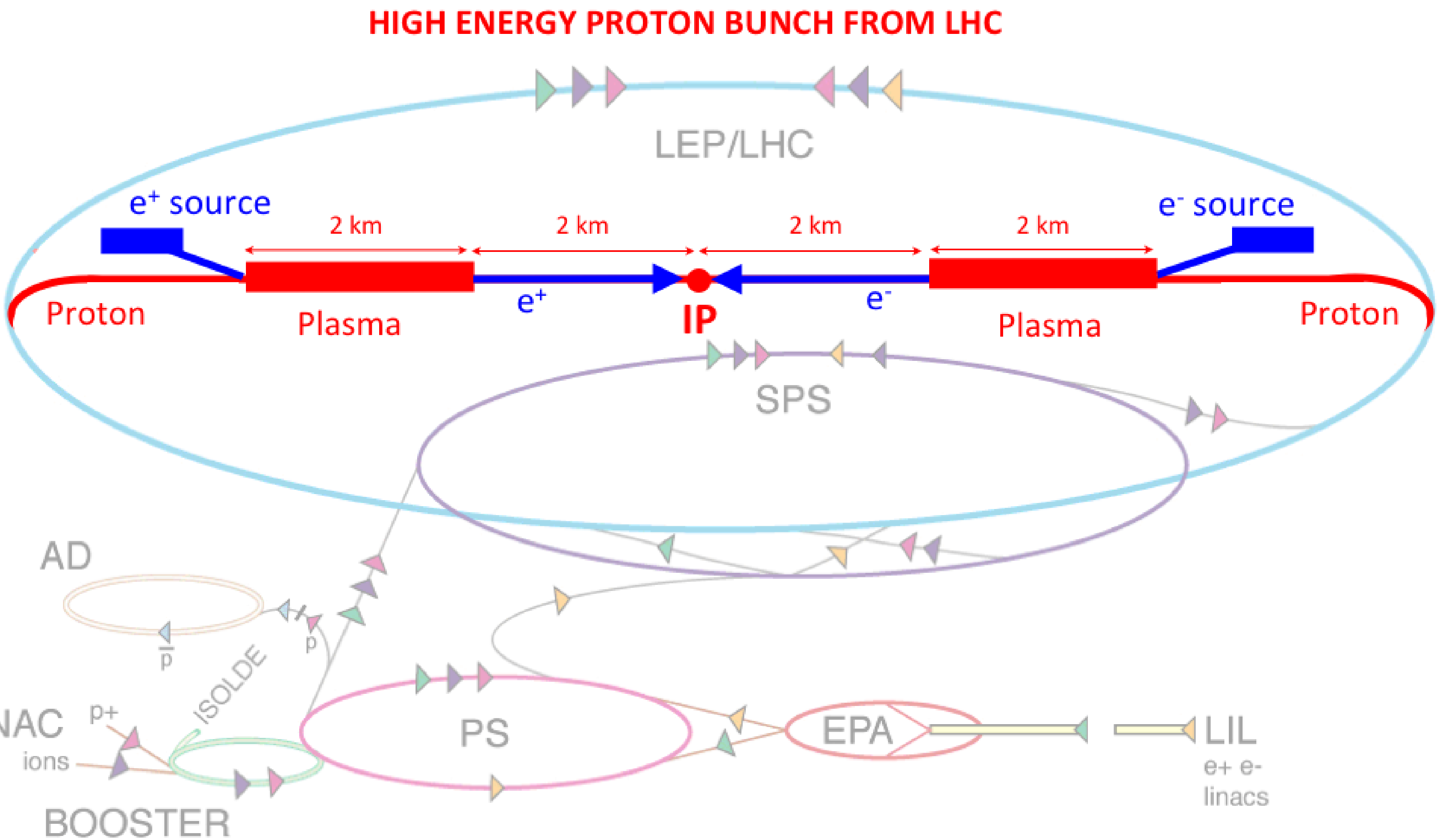
and/or

Electron-proton collider based in PDPWA

Following based on

Collider design issues based on proton-driven plasma wakefield acceleration G. Xia et al.,http://dx.doi.org/10.1016/j.nima.2013.11.006

An electron-positron collider



Layout is not to scale.

An electron-positron collider

Table 1: Parameters of particle beams in present and planned facilities.

	FACET	ILC	CLIC	SPS	Tevatron	LHC
Beam energy (GeV)	25	250	1500	450	1000	7000
Luminosity (10^{34} $cm^{-2}s^{-1}$)	-	2	6	-	0.04	1
Bunch intensity (10^{10})	2.0	2.0	0.372	13	27	11.5 x 10%
Bunches per beam	1	2625	312	288	36	2808
IP bunch length (μm)	30	300	30	1.2E5	350	7.5E4
IP beam sizes σ_x^*/σ_y^* (nm)	1.4E4/6.0E3	474/5.9	40/1	200	3.3E4	1.6E4
Rep rate (Hz)	1	5	50	-	1	1
Stored bunch energy (kJ)	0.08	0.8	0.89	9.4	43	129
Beam power (W)	80	1.05E7	1.39E7	-	5.49E7	3.62E8

Lepton Machines Hadron Machines

Assuming CLIC beam sizes at the IP, 10% drive/witness intensity ratio,

...and 20 mins LHC ramping time, half of LHC bunches, 1 Hz witness bunch repetition rate.

Luminosity of an e^+/e^- collider based on PDPWA ➟ 3 x 10^{31} cm^{-2} s^{-1}

Are there fundamental particle physics topics for high energy but low luminosity ?

Important discussion – power requirements of future colliders critical …

Some examples here:

- growth of QCD scattering cross section with energy: sensitivity via energy dependence to physics at very high energy scales ?

- could a similar effect also happen in electroweak scattering ?
Classicalization and the black hole – particle duality

Electron Proton Scattering in the Proton Rest Frame

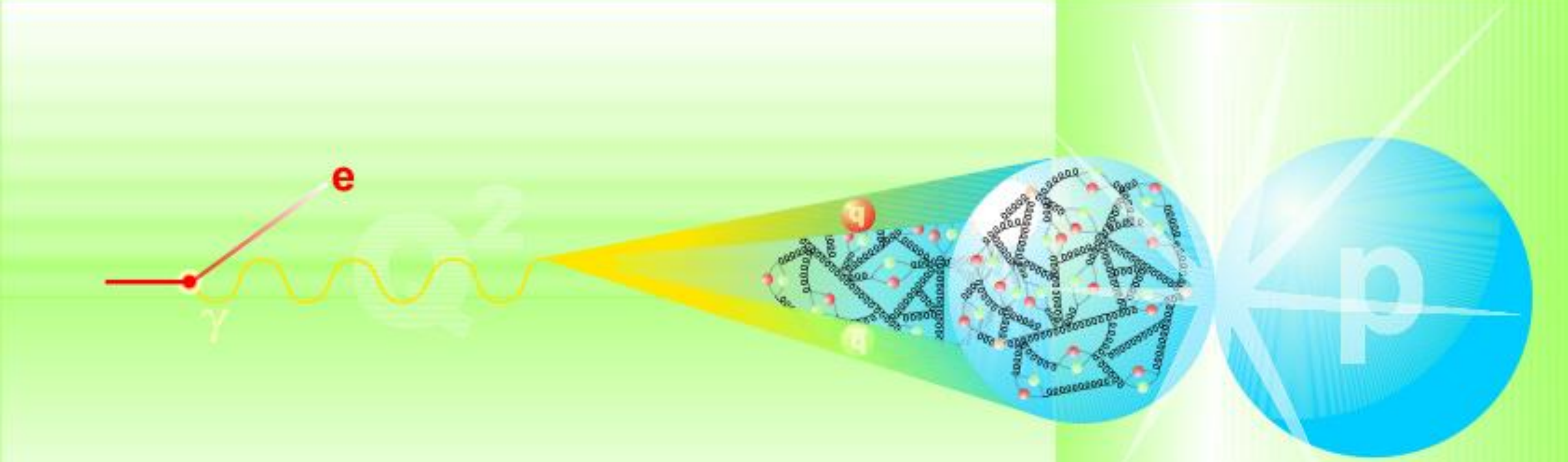
$$\Delta E_\gamma = \sqrt{P_\gamma^2 + M_X{}^2} - \sqrt{P_\gamma^2 + q^2} \approx \frac{Q^2}{E_\gamma} \qquad M_X = Q$$

$$E_\gamma = W^2/2M_P \qquad \Delta E_\gamma \approx \frac{2M_P Q^2}{W^2} \qquad l \approx \frac{0.2\, fm}{2M_P x}$$

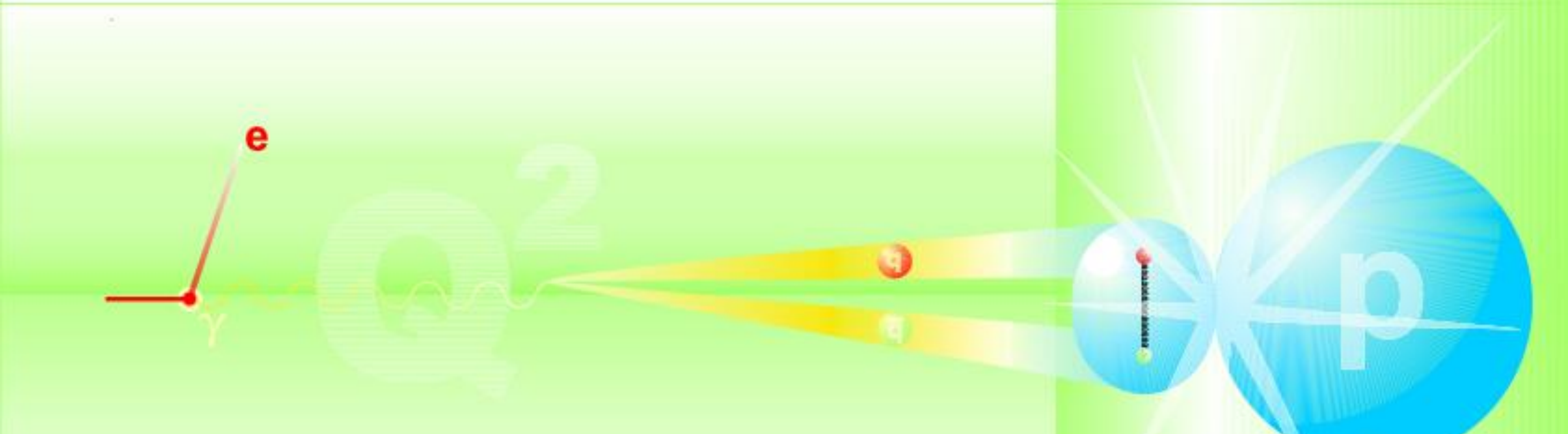
So, small-x means long-lived photon fluctuations (not proton structure)

HERA collider physics H. Abramowicz (Tel Aviv U.) , A. Caldwell (Columbia U.)
Rev.Mod.Phys. 71 (1999) 1275-1410

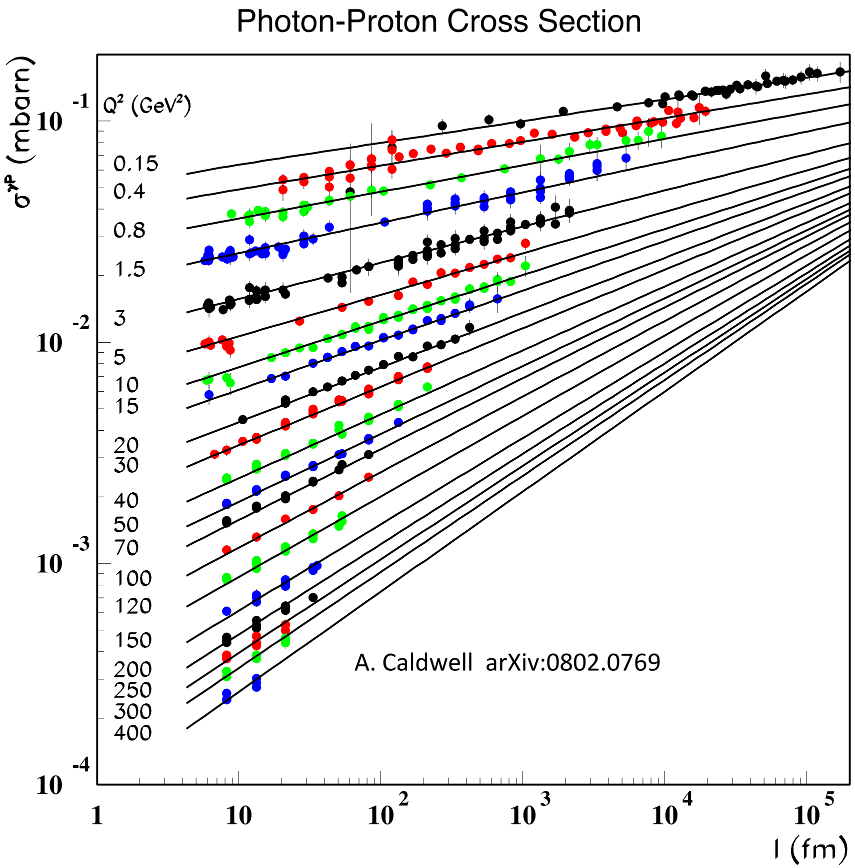
Another common project …

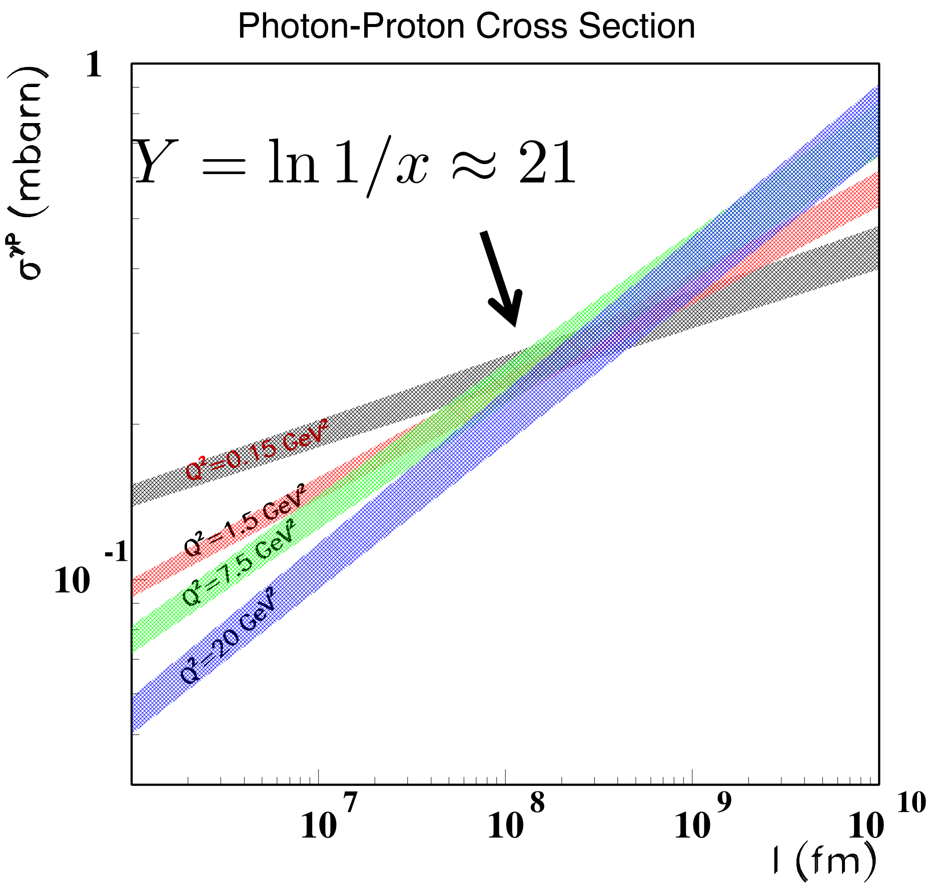


Small-x, small Q^2



Larger-x, larger Q^2





Slope of the cross section with l increases with Q^2. Extrapolation of the cross section with fixed slope.

Can we probe this behavior at higher energies ?

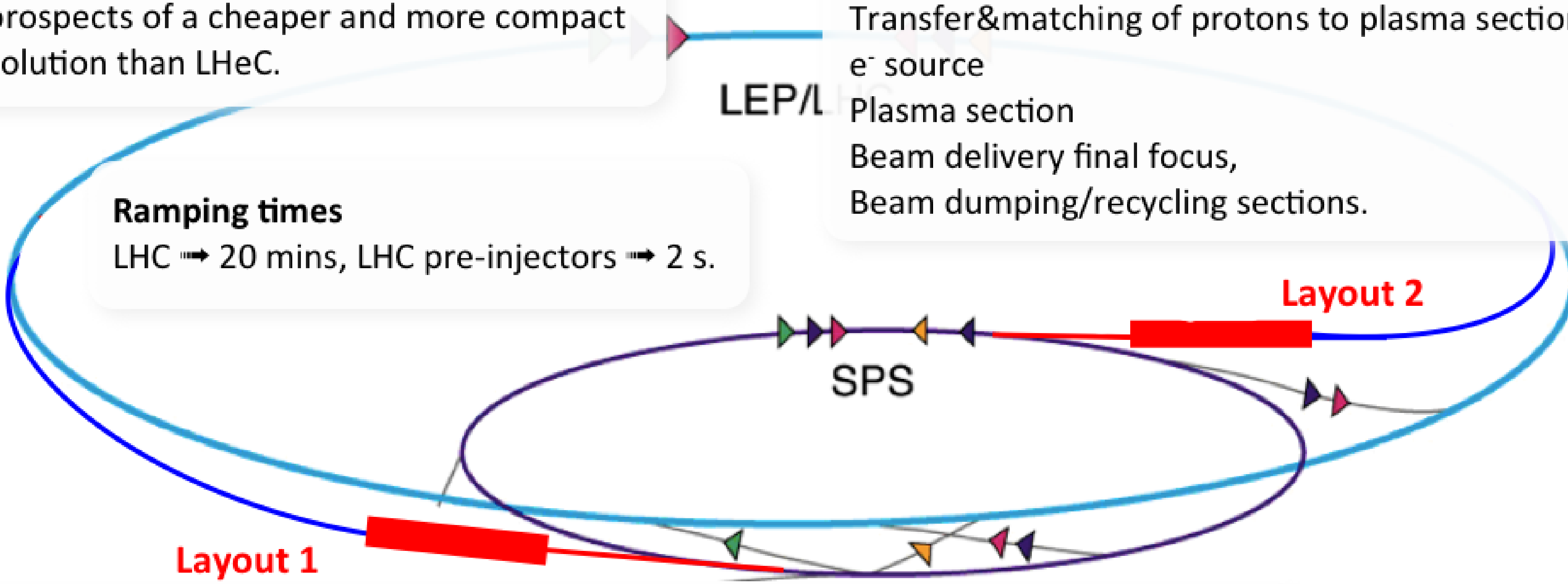
An electron-proton collider

TWO EXAMPLE LAYOUTS

Utilisation of existing CERN infrastructure
prospects of a cheaper and more compact solution than LHeC.

Basic sub-systems
Transfer&matching of protons to plasma section,
e^- source
Plasma section
Beam delivery final focus,
Beam dumping/recycling sections.

Ramping times
LHC ➟ 20 mins, LHC pre-injectors ➟ 2 s.



SPS protons can excite the plasma during LHC ramping
PIC simulations: 1 GeV m^{-1} ➟ accelerates e^- beam up to 100 GeV in 170 m of plasma.

Parasitic e^-p collisions*
establish collisions between 100 GeV e^- beam and 7 TeV LHC protons.
*LHC collisions can continue in parallel

$$\mathcal{L} \sim 10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Conclusions

Accelerator based particle physics has had a tremendous impact on our knowledge and has been the key to the development of the Standard Model of particle physics.

But, we are in need of novel ideas …

Plasma Wakefield Acceleration has been proposed many years ago – steady progress in developing the technology, but there is still a long way to go. Investigate new option – proton-driven PWA.

Expect interesting results within the next 5 years – stay tuned

Dear Halina,

Happy Birthday !