MAX-PLANCK-GESELLSCHAFT

Linear Collider Technologies ILC, CLIC and Plasma Wakefield Acceleration

Lecture at

Linear Collider School

Frauenchiemsee 15-August-2014

Allen Caldwell

Max Planck Institute for Physics, Munich

$\Delta p \cdot \Delta q \geq \frac{1}{2}\hbar$

Max-Planck-Institut für Physik

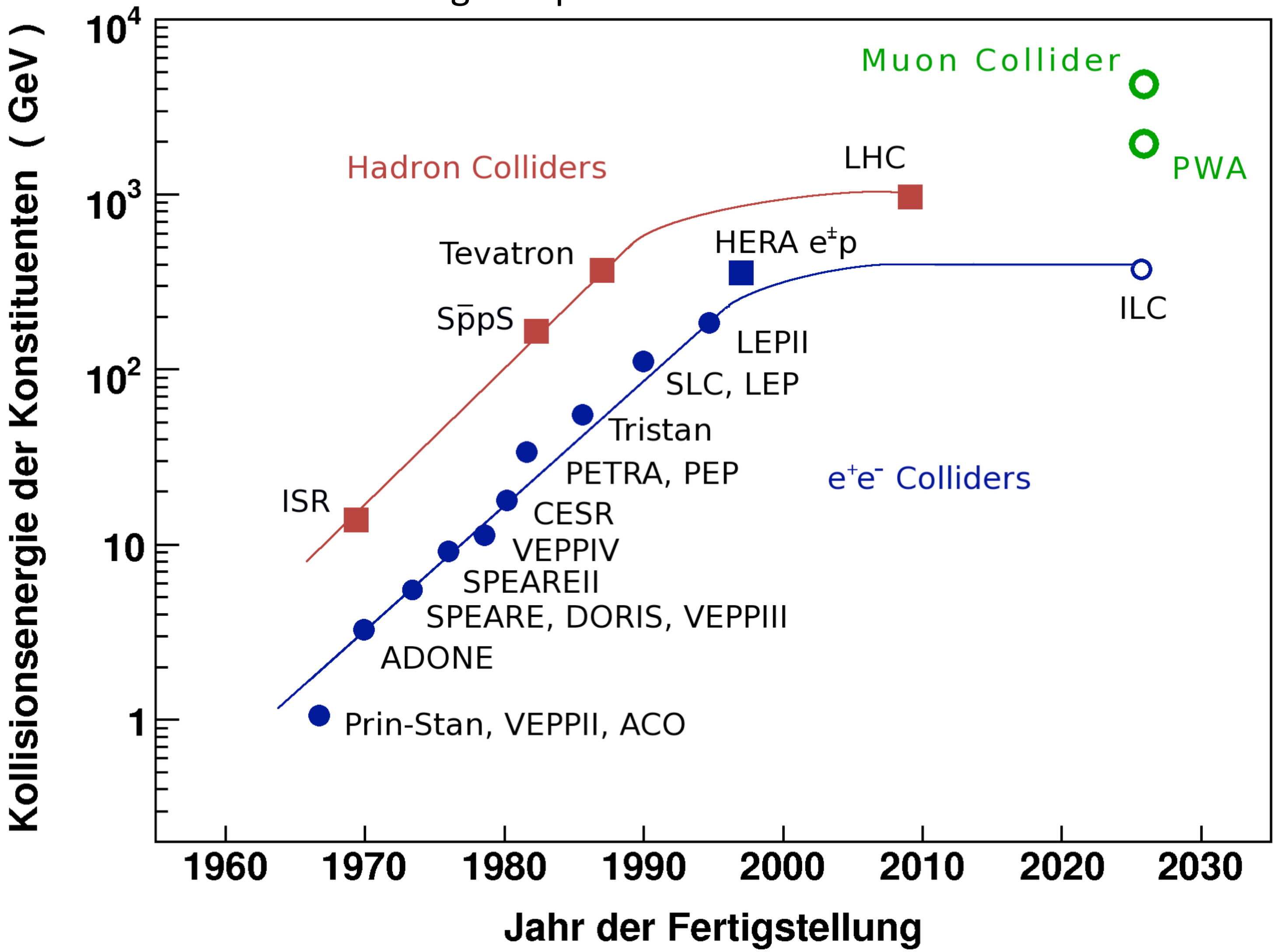
(Werner-Heisenberg-Institut)

Apology

There are many people here who know a lot more about the ILC and CLIC Technology than I do, so I will focus more on the Plasma Wakefield Acceleration …

But, I have 'borrowed' some material from nice lectures by Nick Walker at last year's school, and from ICHEP as well as material from Steinar Stapnes from a DESY seminar.

The Livingston plot shows a saturation …

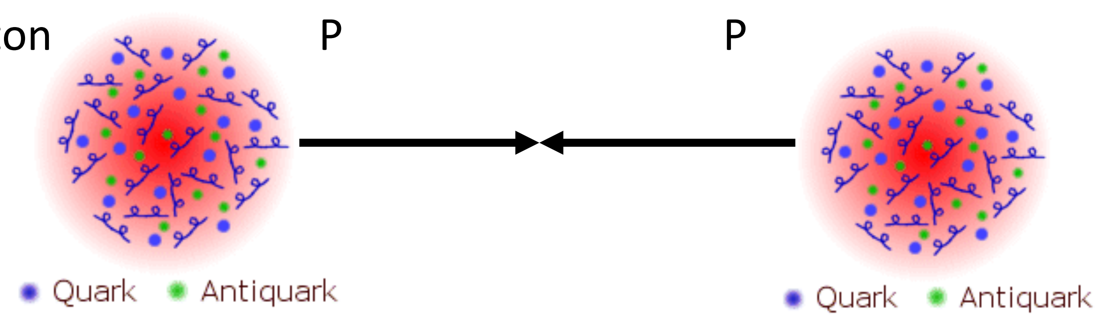


Practical limit for accelerators at the energy frontier: Project cost increases as the energy must increase! New technology needed…

A. Caldwell

Future Lepton Collider

proton

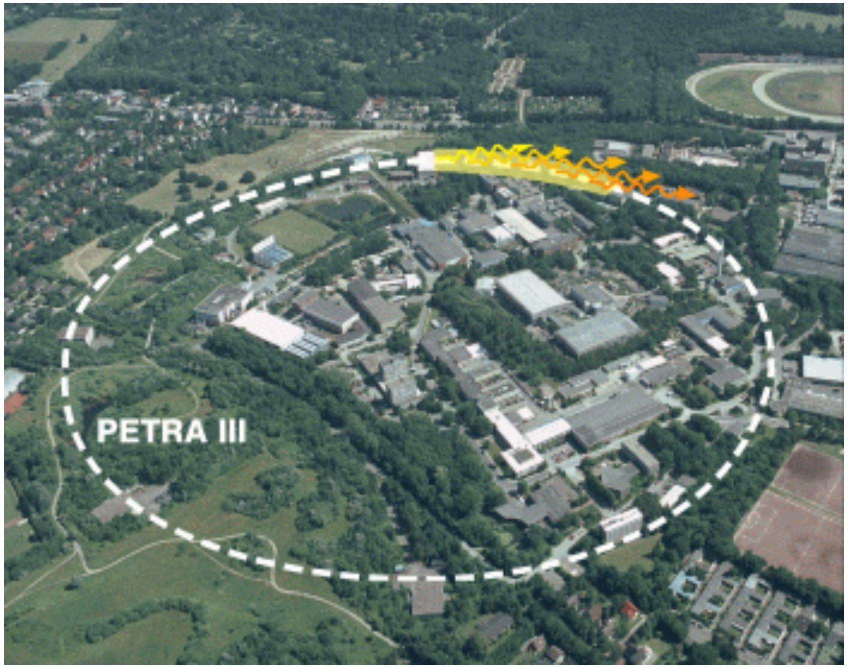


Leptons preferred:
Collide point particles rather than complex objects

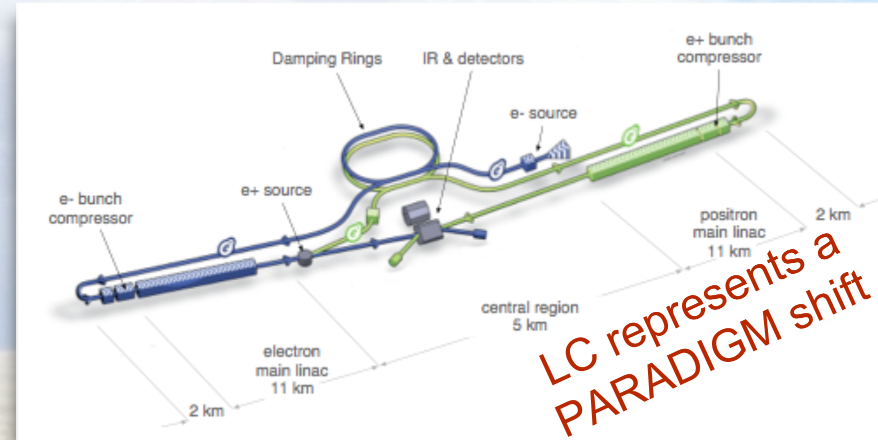
But, charged particles radiate energy when accelerated.

Power α $(E/m)^4$

Need linear electron accelerator !
Muon Collider can be circular.



INTERNATIONAL LINEAR COLLIDER



- **200-500 GeV cm (extendable to 1 TeV)**
  - L ~ 1.8×10^{34} $cm^{-2}s^{-1}$ (@ 500GeV)
  - 7.8 Billion ILCU + 23 Million p-hrs
- **>20 years R&D worldwide**
  - A truly global effort
  - Over 2,000 man years
  - >300 M$ globally

- **Cost driver: SRF technology**
  - 17,000 1.3 GHz Nb cavities
  - 1,800 cryomodules
- **Mature SRF technology**

From N. Walker

1.3 GHz Superconducting RF Cavity

- solid niobium
- standing wave
- 9 cells
- operated at 2K (LHe)

- 35 MV/m
- $Q_0 \geq 10^{10}$

A. Caldwell

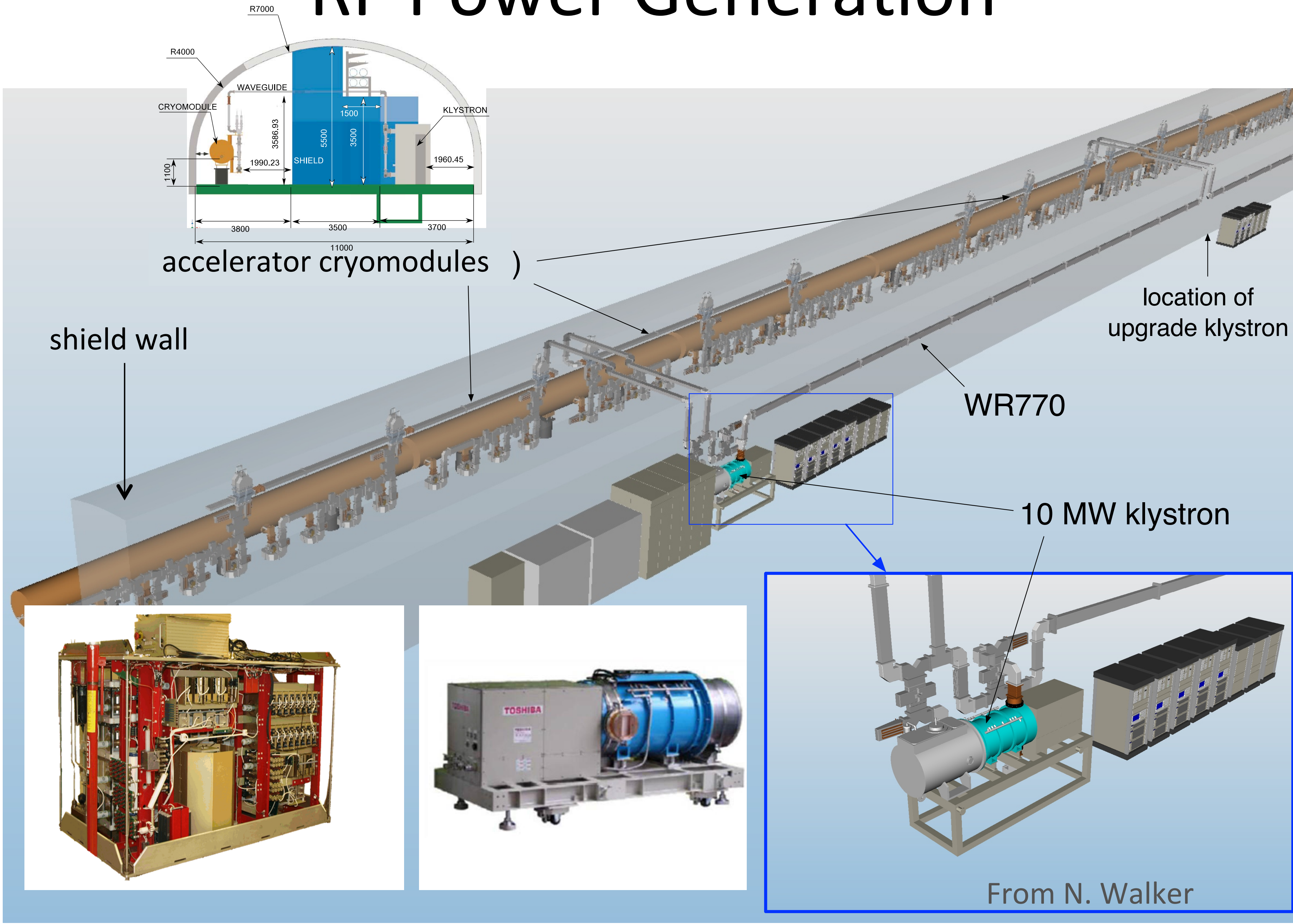
From N. Walker

Why SCRF

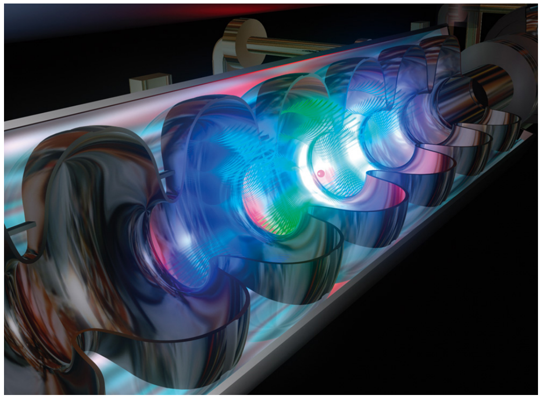
- High RF → Beam-power efficiency
  - low-loss cavities
- Ease of RF power generation
  - low frequency (1.3 GHz)
  - Long pulse / fill time
- Emittance preservation
  - Large cavity iris
  - low transverse and longitudinal wakefields

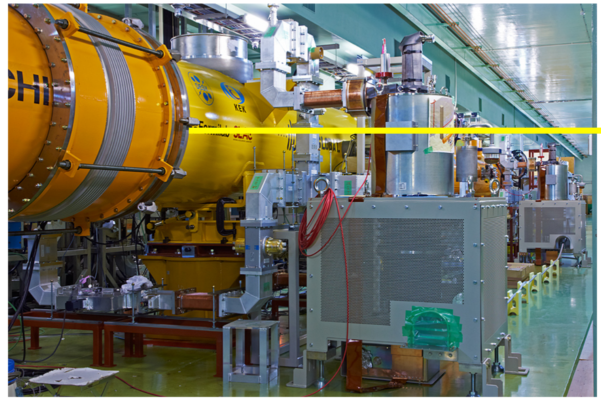
From N. Walker

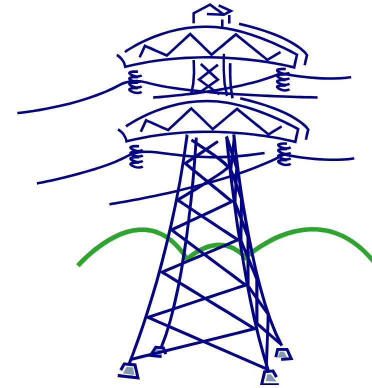
RF Power Generation



AC Power (Linac)







$$P_{beam} = V_{acc} \times I_{beam} \approx 20 \text{ MW}$$

RF Power Generation
(Modulator, klystron,
Waveguide distribution)

Wall Plug

$$\eta_{RF \to beam} = \frac{t_{beam}}{t_{beam} + t_{fill}} \approx 60\%$$

Cryogenic
Power
33 MW

$\eta \approx 44\%$

$P_{RF} \approx 32$ MW

$P_{AC(RF)} \approx 76$ MW

132 MW

to beam dump

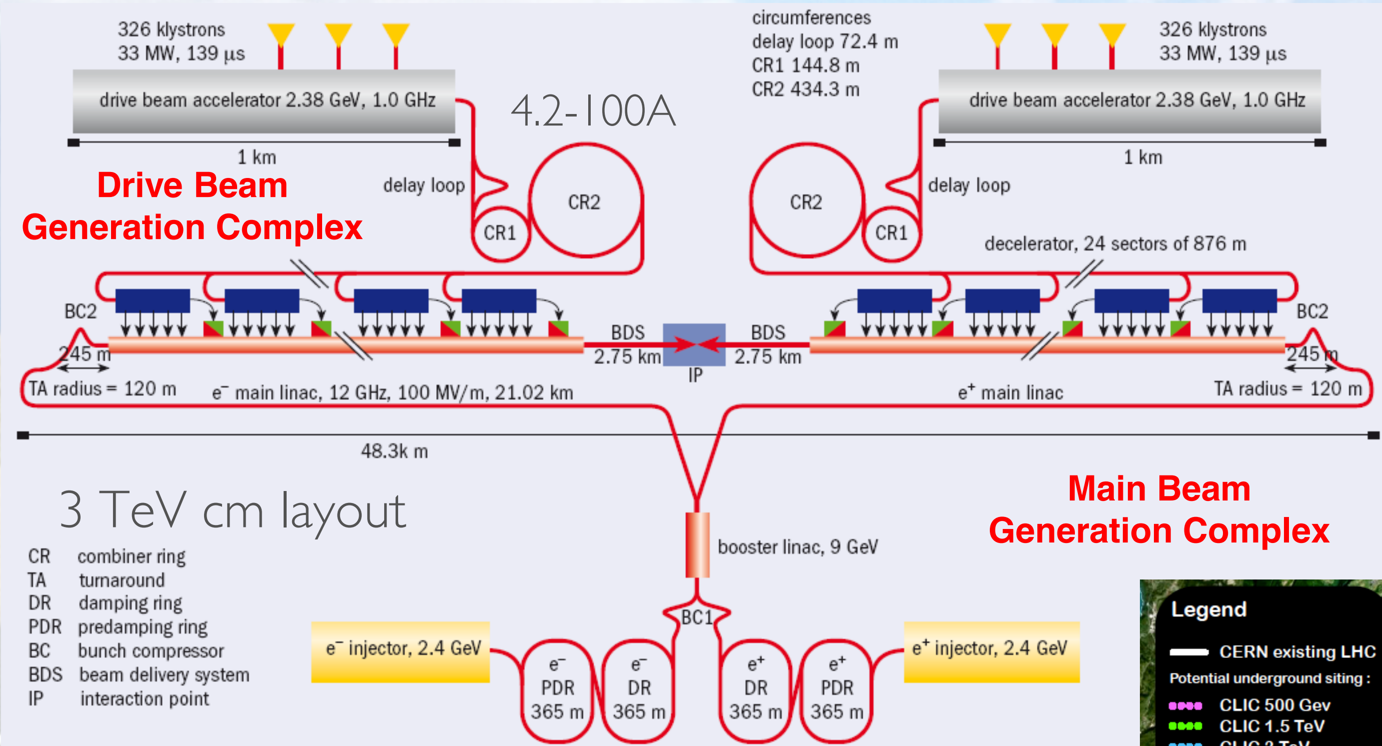
$$\boxed{t_{fill} \propto \frac{V_{acc}}{I_{beam}}}$$

56 MW to remove!

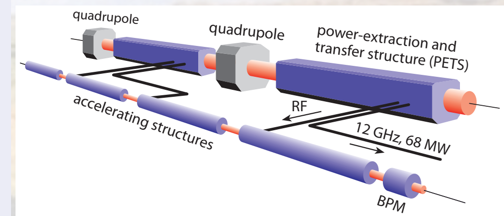
+24 MW water (CF)

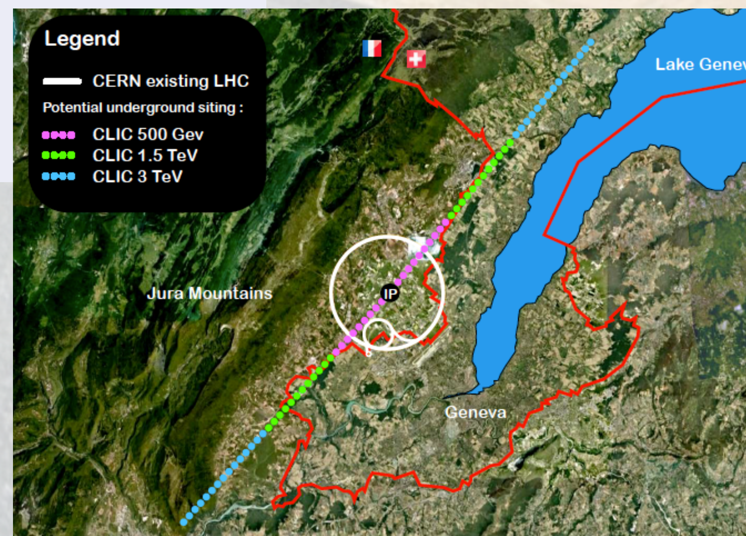
From N. Walker

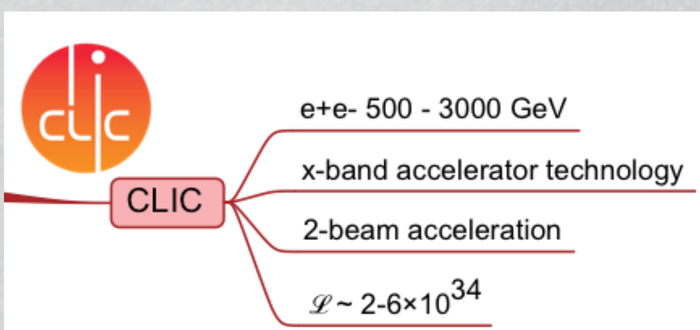
Compact LInear Collider (CLIC)



$G_a \sim 100$ MV/m



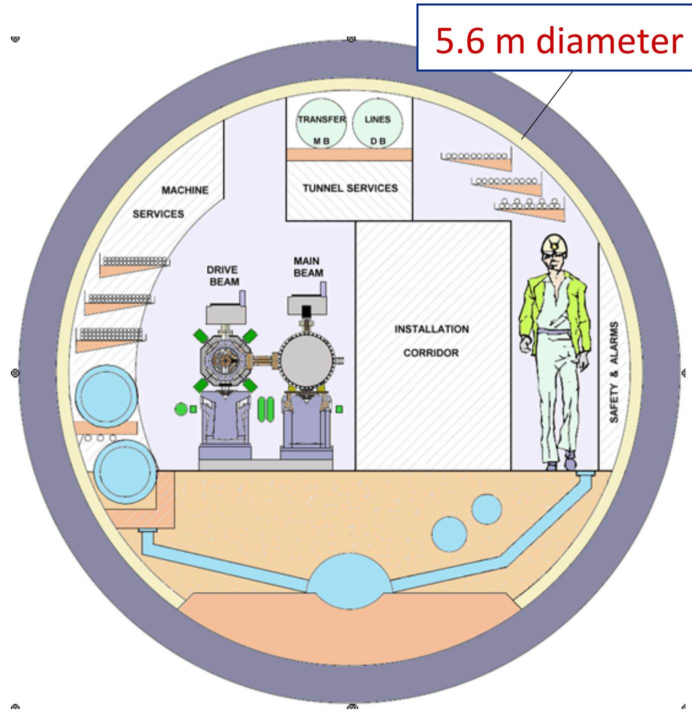




0.5 TeV: 8,300 MCHF ($\mathscr{L} \sim 1.4\times10^{34}$)
From N. Walker

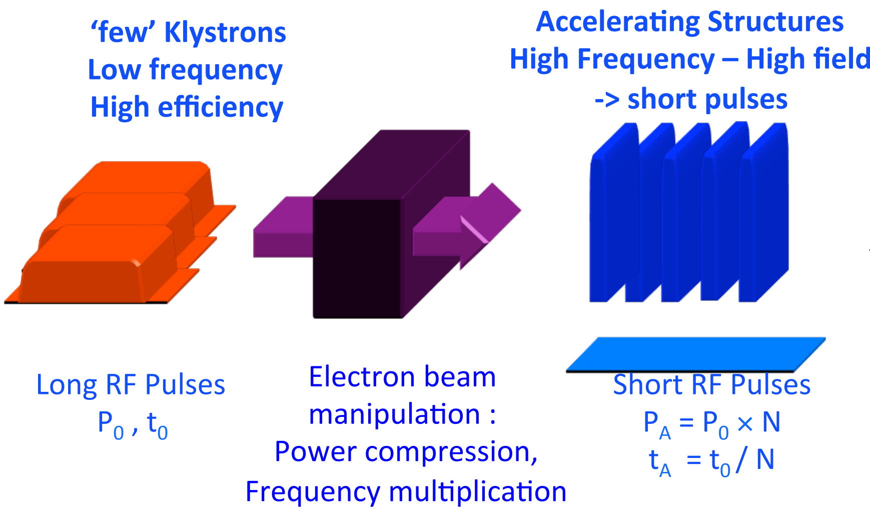
Compact Linear Collider - CLIC

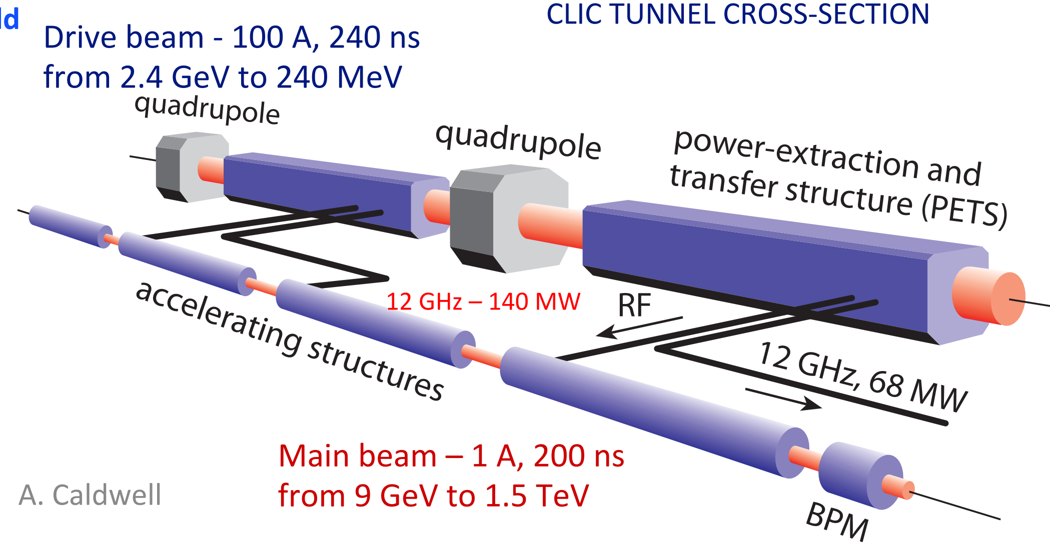
- High acceleration gradient: > 100 MV/m
  - Compact collider: total length < 50 km at 3 TeV
  - Normal conducting acceleration structures at high RF frequency (12 GHz)
- Novel Two-Beam Acceleration Scheme
  - Cost effective, reliable, efficient
  - Single tunnel, no active power components
  - Modular, staged energy upgrade



CLIC TUNNEL CROSS-SECTION

Compact rf pulses: by e- compression





A. Caldwell

From S. Stapnes

Possible CLIC stages studied

Table 1: Parameters for the CLIC energy stages of scenario A.

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	500	1400	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		354	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	80	80/100	100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	2.3	3.2	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	1.4	1.3	2
Main tunnel length		km	13.2	27.2	48.3
Charge per bunch	N	10^9	6.8	3.7	3.7
Bunch length	σ_z	μm	72	44	44
IP beam size	σ_x/σ_y	nm	200/2.6	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	2350/20	660/20	660/20
Normalised emittance (IP)	$\varepsilon_x/\varepsilon_y$	nm	2400/25	—	—
Estimated power consumption	P_{wall}	MW	272	364	589

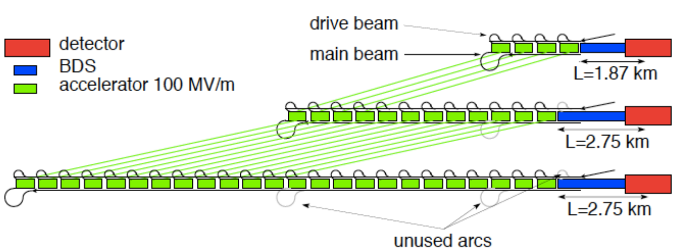


Fig. 3.6: Simplified upgrade scheme for CLIC staging scenario B.

Table 2: Parameters for the CLIC energy stages of scenario B.

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	500	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		312	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	100	100	100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	1.3	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	0.7	1.4	2
Main tunnel length		km	11.4	27.2	48.3
Charge per bunch	N	10^9	3.7	3.7	3.7
Bunch length	σ_z	μm	44	44	44
IP beam size	σ_x/σ_y	nm	100/2.6	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	—	660/20	660/20
Normalised emittance	$\varepsilon_x/\varepsilon_y$	nm	660/25	—	—
Estimated power consumption	P_{wall}	MW	235	364	589

Key features:

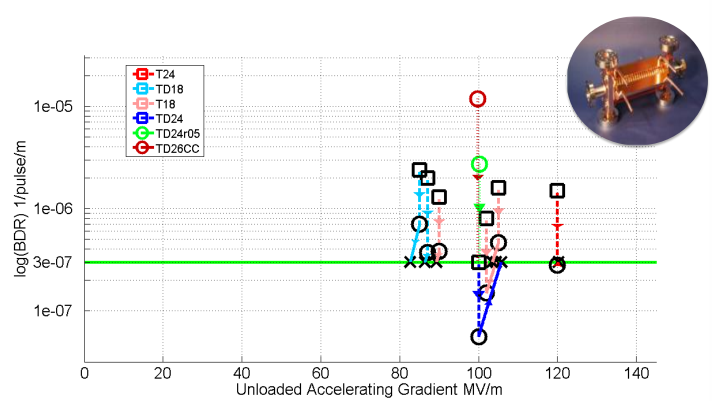
- High gradient (energy/length)
- Small beams (luminosity)
- Repetition rates and bunch spacing (experimental conditions)

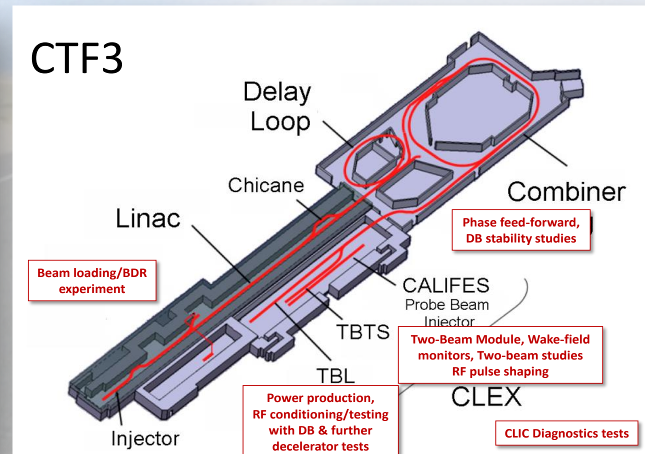
From S. Stapnes

Compact LInear Collider (CLIC)

>20 years of R&D
CDR published in 2012
Currently undergoing rebaselining (→ 2018)

High-gradient structure tests





Currently the only option to multi-TeV e^+e^-

ATF2 (KEK)
- nanobeams, stabilisation

FACET (SLAC)
- emittance preservation / tuning

Synergy with ILC

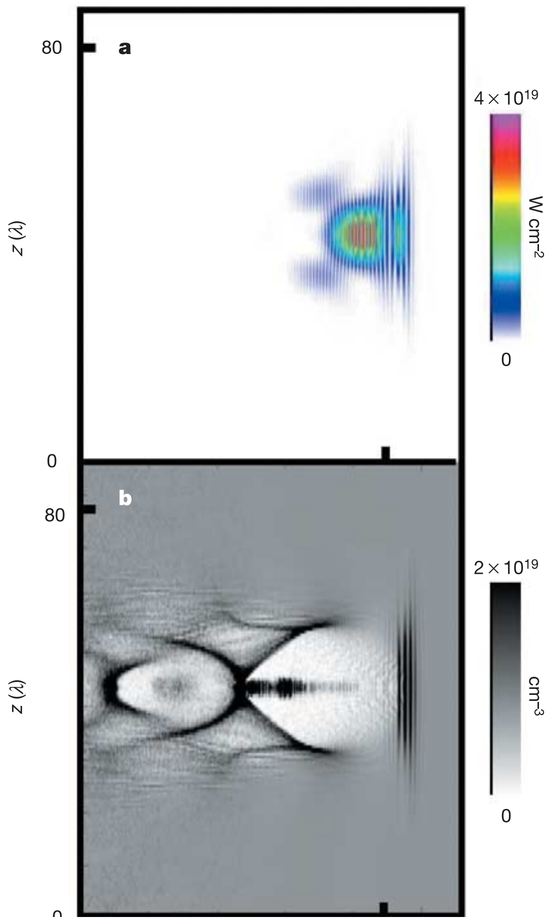
2012-2018 programme:
- rebaselining (cost, MW, E_{cm} staging)
- Further high-gradient R&D
- Systems testing (CTF3,ATF2,FACET)
- Tech. systems development (CLIC module)
- Physics studies…

From S. Stapnes

Plasma Wakefield Acceleration

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

Figure from
J. Faure et al.,
Nature **43**



Plasma frequency depends only on density:

$$\omega_p^2 = \frac{4\pi n_p e^2}{m}$$

$$k_p = \frac{\omega_p}{c}$$

$$\lambda_p = \frac{2\pi}{k_p} = 1mm\sqrt{\frac{1 \cdot 10^{15}\ \mathrm{cm}^{-3}}{n_p}}$$

Produce an accelerator with mm (or less) scale 'cavities'

100 GeV/m acceleration demonstrated !

But – Acceleration is ***DEPLETION-LIMITED***

i.e., the lasers do not have enough energy to accelerate a bunch of particles to very high energies

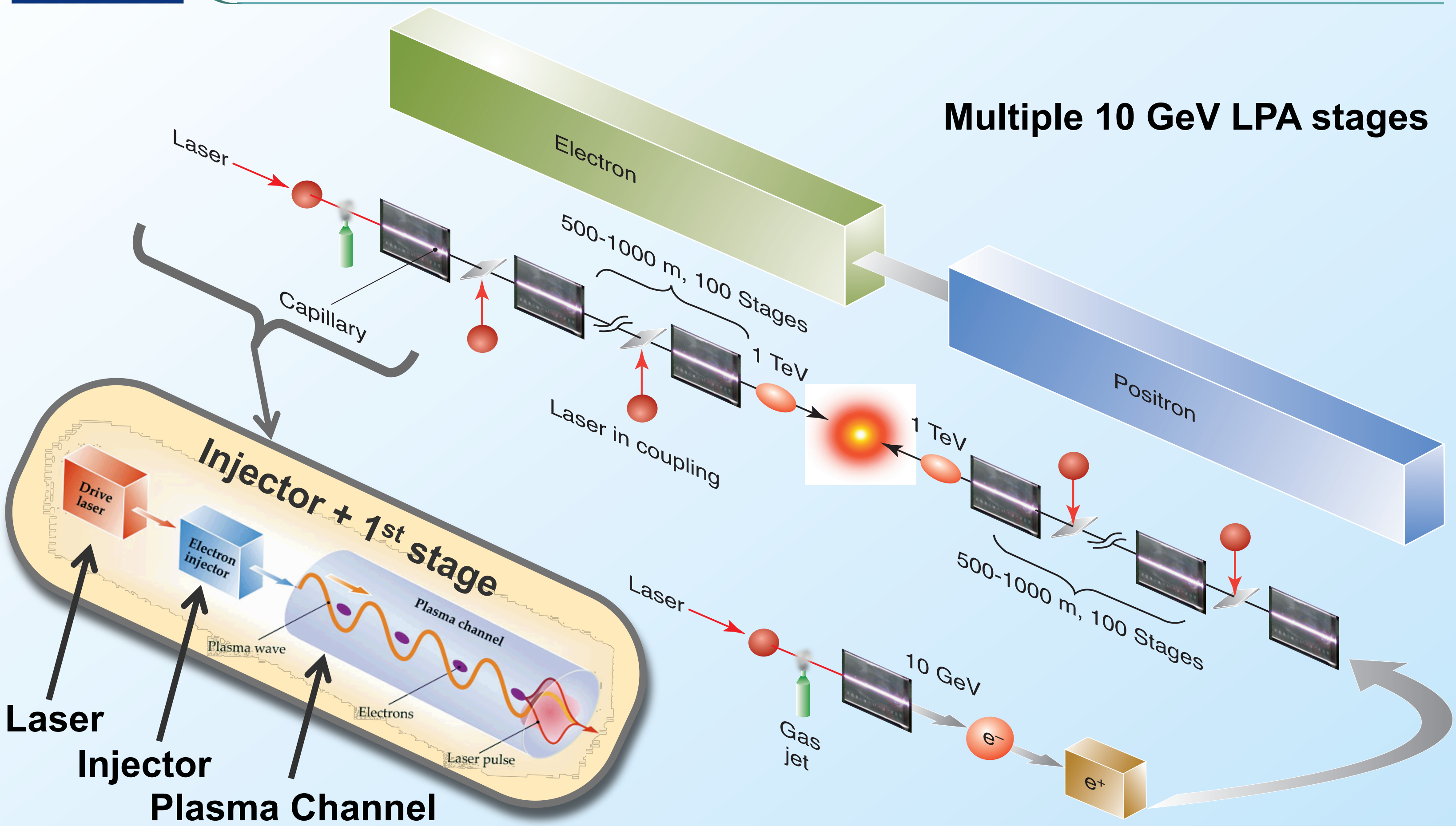
e.g.,

$$10^{10}\ \mathrm{electrons} \cdot 10^{12}\ \mathrm{eV} \cdot 1.6 \cdot 10^{-19}\ \mathrm{J/eV} = kJ$$

This is orders of magnitude larger than what can be done today.

If use several lasers – need to have relative timing in the 10's of fs range

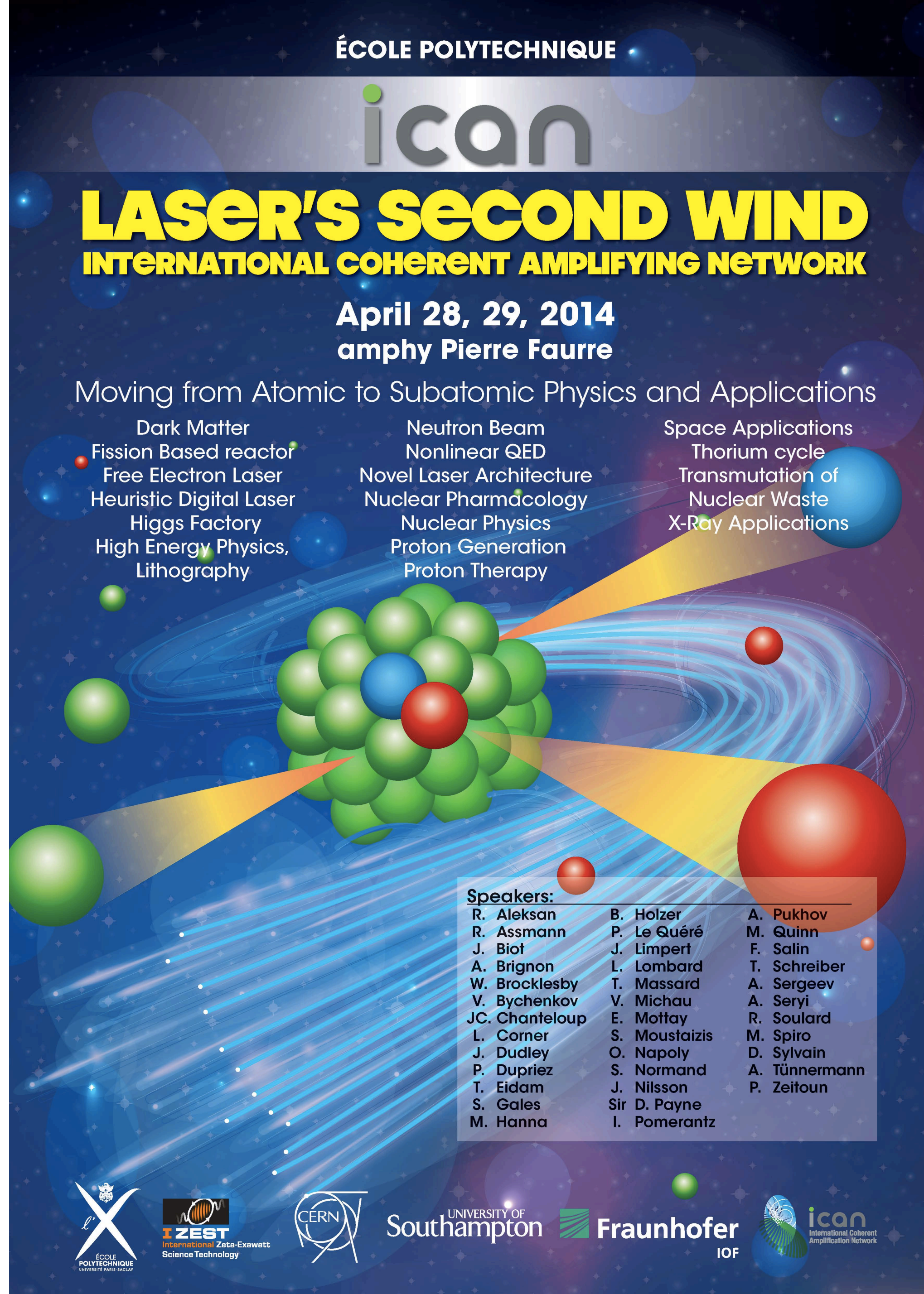
Strawman Design of a TeV LPA Collider



Leemans & Esarey, Physics Today, March 2009

There are very interesting developments ongoing in the Laser community that could have great impact on a future Laser Driven PWA.

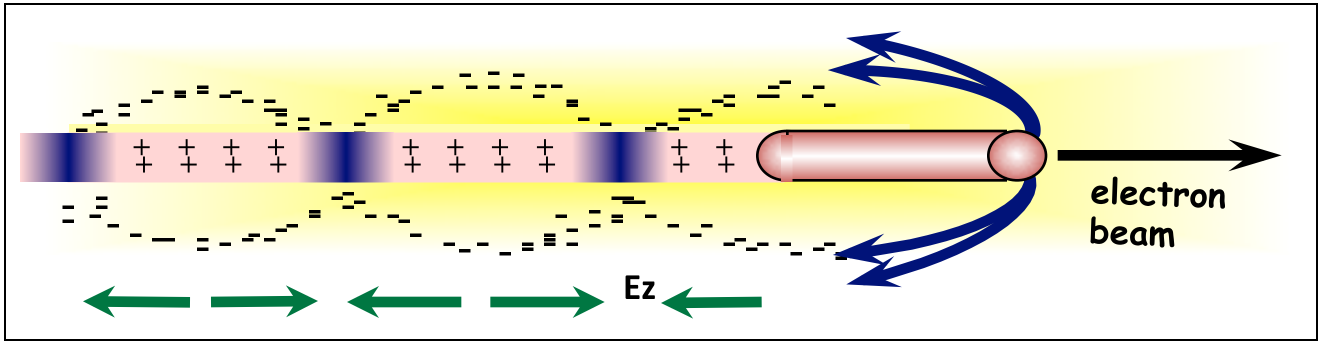
IZEST/ICAN



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



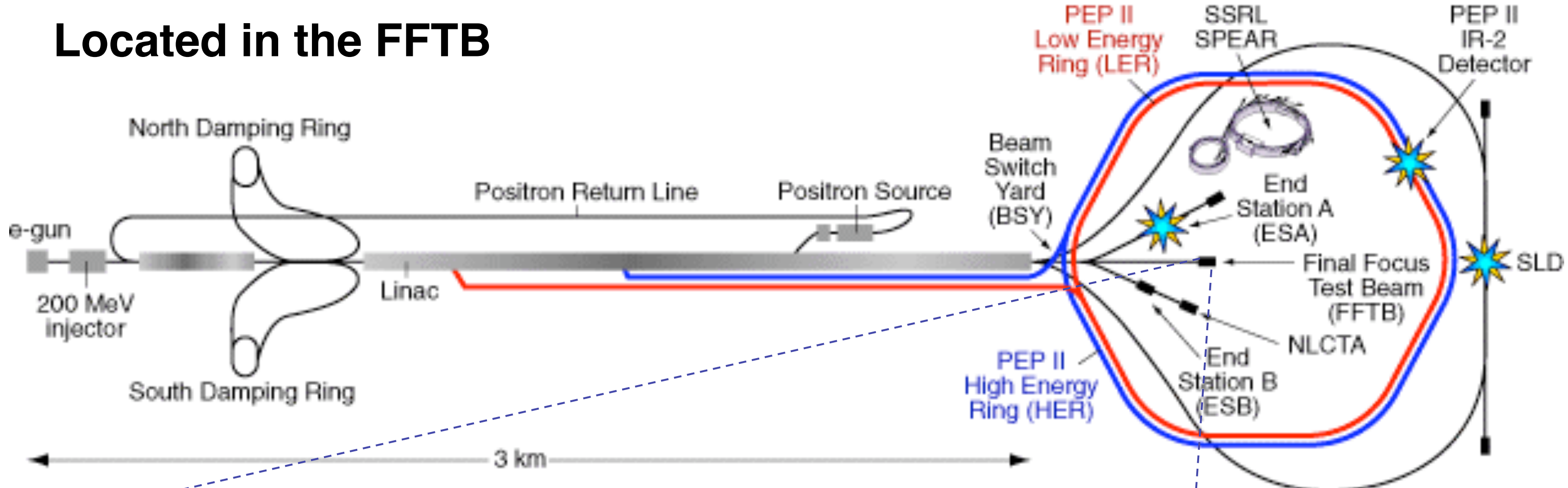
Electric fields can accelerate, decelerate, focus, defocus

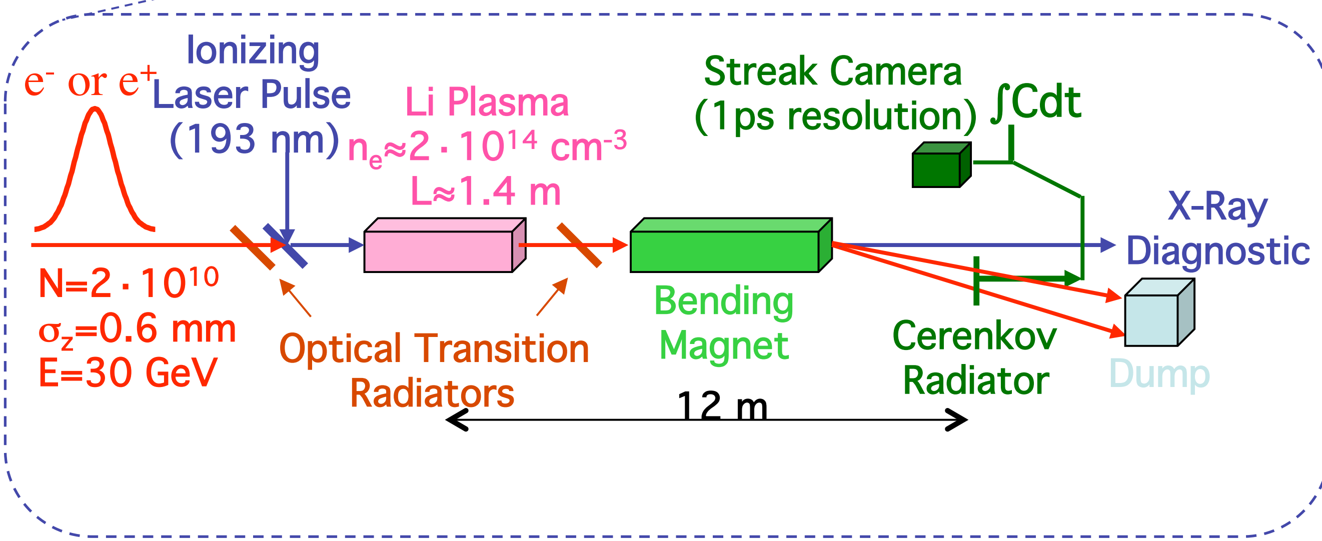
Plasma also provides super-strong focusing force !
(many thousand T/m in frame of accelerated particles)

A. Caldwell

Experimental Layout (E-157)

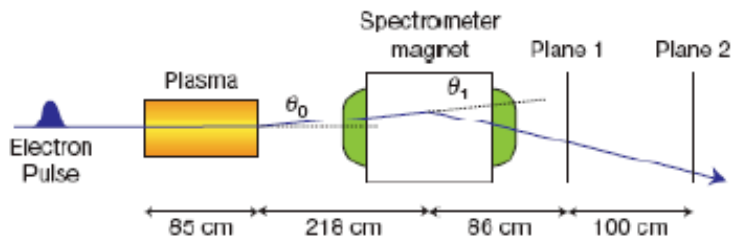
Located in the FFTB



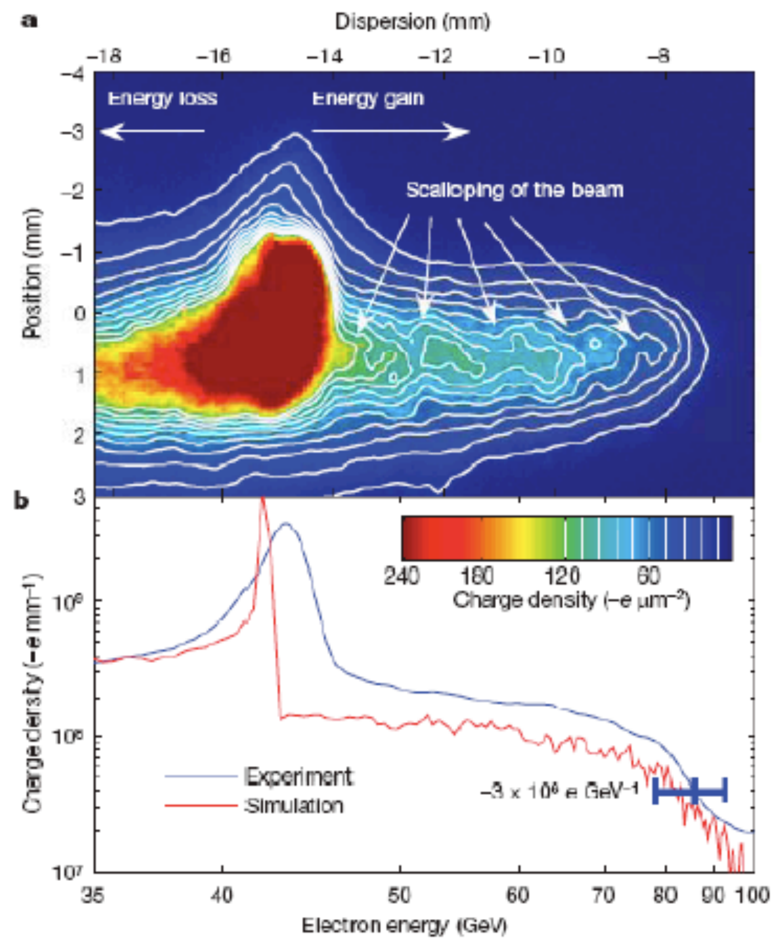


A. Caldwell

Highlight: latest SLAC/UCLA/USC results
(Nature 2007)



SLAC beam
- 42 GeV
- 3 nC @ 10 Hz
- focused to 10 μm spot size
- compressed to 50 fs



- Some electrons double their energy: from 42 to > 80 GeV
- E=50 GV/m over 0.8 meters

I. Blumenfeld et al., Nature **445**, 741 (2007)

Are electrons the obvious drivers ???

There is a limit to the energy gain of a trailing bunch in the plasma:

$$R = \frac{\Delta T^{\rm witness}}{\Delta T^{\rm drive}} \leq 2 \quad \text{T is the kinetic energy}$$

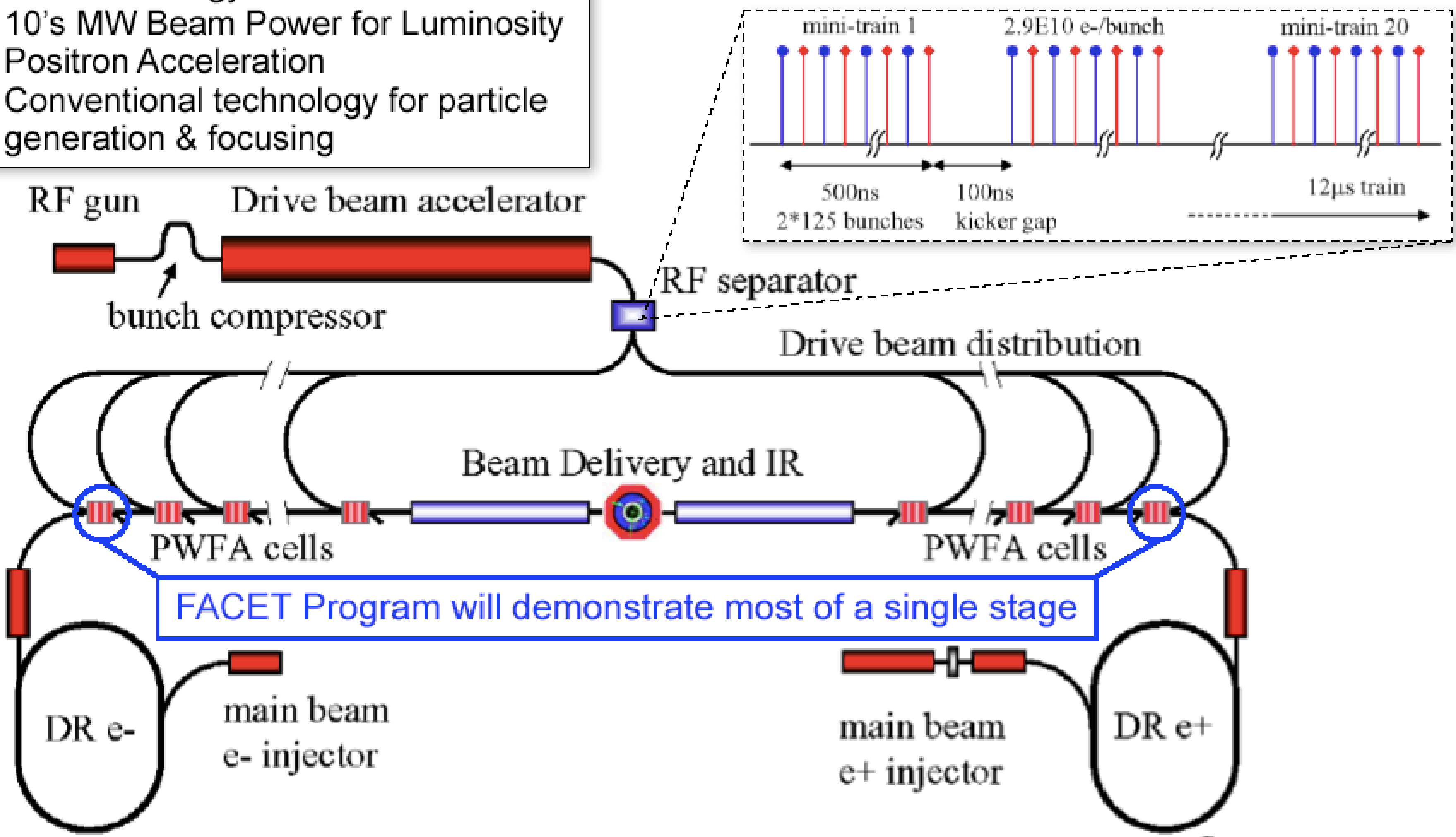
(for longitudinally symmetric bunches).

See e.g. SLAC-PUB-3374, R.D. Ruth et al.

This means many stages required to produce a 1TeV electron beam from known electron beams (SLAC has 45 GeV)

A Concept for a Plasma Wakefield Accelerator Based Linear Collider

- TeV CM Energy
- 10's MW Beam Power for Luminosity
- Positron Acceleration
- Conventional technology for particle generation & focusing



Chan Joshi Presentation at SLAC Annual Program Review 2008

Proton Drivers for PWFA

Assuming Gaussian beams:

$$E_{z,\max} = eNk_p^2 \exp\left(-\frac{k_p^2\sigma_z^2}{2} + \frac{k_p^2\sigma_r^2}{2}\right)\Gamma\left(0, k_p^2\sigma_r^2/2\right) ,$$

Linear regime ($n_b<n_0$):

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

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

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

Compression of proton bunch needs to be solved for PDPWA !

Issues with a Proton Driven PWA:

- Small beam dimensions required

$$eE_{linear} = 240(\mathrm{MeV/m})\left(\frac{\mathrm{N}}{4\cdot 10^{10}}\right)\left(\frac{0.6}{\sigma_z(\mathrm{mm})}\right)^2$$

$$\sigma_z = 100\mu m \text{ ,N} = 1\ 10^{11} \text{ yields 21 GeV/m}$$

Can such small beams be achieved with protons ? Typical proton bunches in high energy accelerators have rms length >20 cm

- Phase slippage because protons heavy (move more slowly than electrons)

$$\delta = \frac{\pi L}{\lambda_p}\left[\frac{1}{\gamma_{1i}\gamma_{1f}} - \frac{1}{\gamma_{2i}\gamma_{2f}}\right] \approx \frac{\pi L}{\lambda_p}\left[\frac{M_P^2 c^4}{E_{driver,i}E_{driver,f}}\right]$$

$$L \le \frac{1}{2}\left[\frac{E_{driver,i}E_{driver,f}}{M_P^2 c^4}\right]\lambda_p \approx 300 \text{ m for } E_{driver,i} = 1TeV, E_{driver,f} = 0.5TeV, \lambda = 1mm$$

Few hundred meters possible but depends on plasma wavelength

Issues with a Proton Driven PWA continued:

- Longitudinal growth of driving bunch due to energy spread

$$d = \Delta v \cdot t \approx \Delta\beta \cdot L = \left(\gamma_1^{-2} - \gamma_2^{-2}\right)L \approx 2\left(\frac{\Delta E}{E}\right)\frac{M_P^2 c^4}{E^2} L$$

$$\text{For } d = 100\mu m, \quad L = 100m, \quad E = 1.TeV, \quad \frac{\Delta E}{E} = 0.5$$

Large momentum spread is allowed !

Issues - continued

- Proton interactions

$$\lambda = \frac{1}{n\sigma} < \frac{1}{n(10^{-23}\ \mathrm{cm}^2)} \qquad n = 1 \cdot 10^{15} cm^{-3} \quad \Rightarrow \quad \lambda = 1000\ \mathrm{km}$$

Only small fraction of protons will interact in plasma cell

Biggest issue identified so far is proton bunch length.

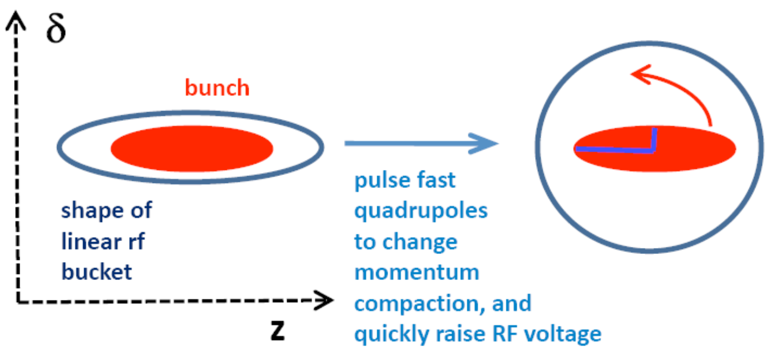
Need large energies to avoid phase slippage because protons are heavy.

Large momentum spread is allowed.

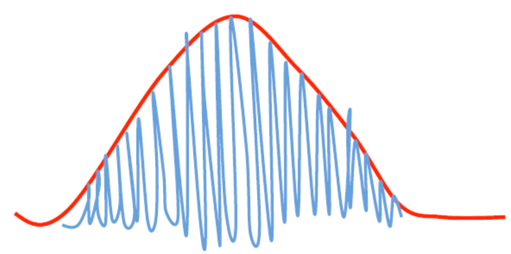
Bunch Compression

Producing a short proton bunch is critical. Different ideas are under investigation.

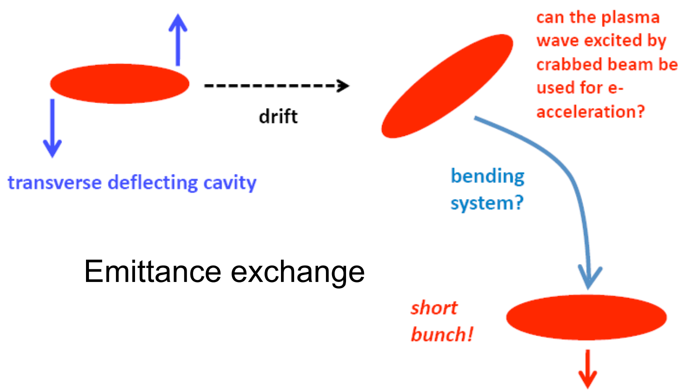
Short proton bunch production



Schematics of fast bunch rotation in storage ring



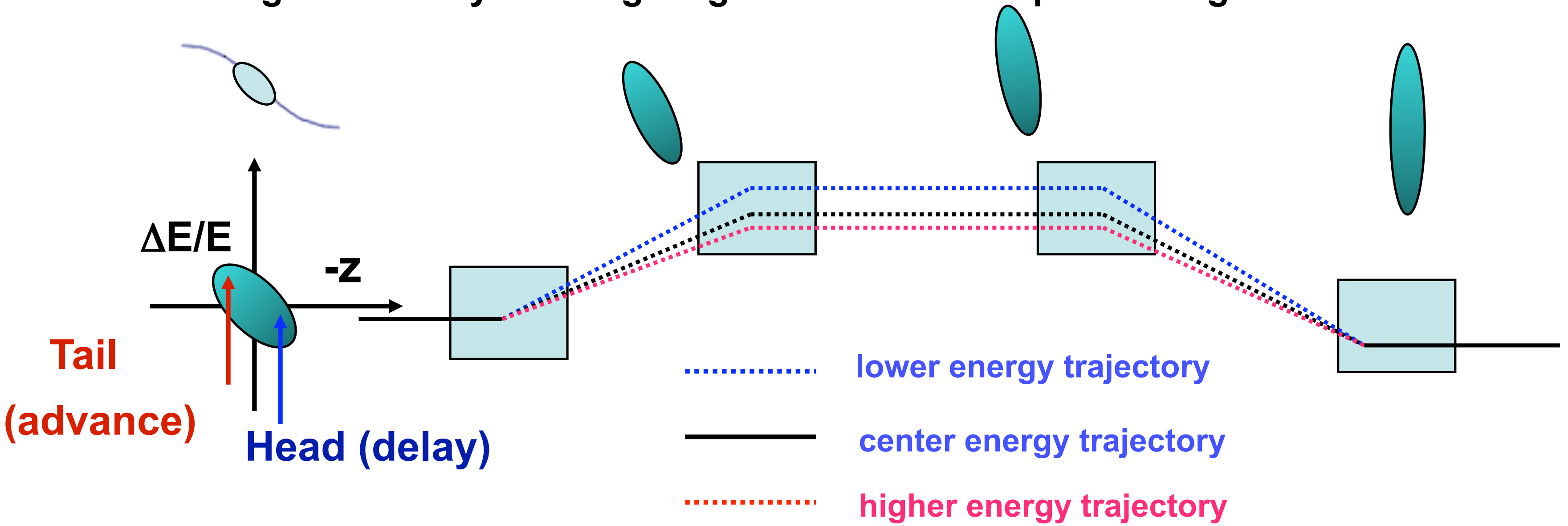
Nanochopper gets the microbunch



Emittance exchange

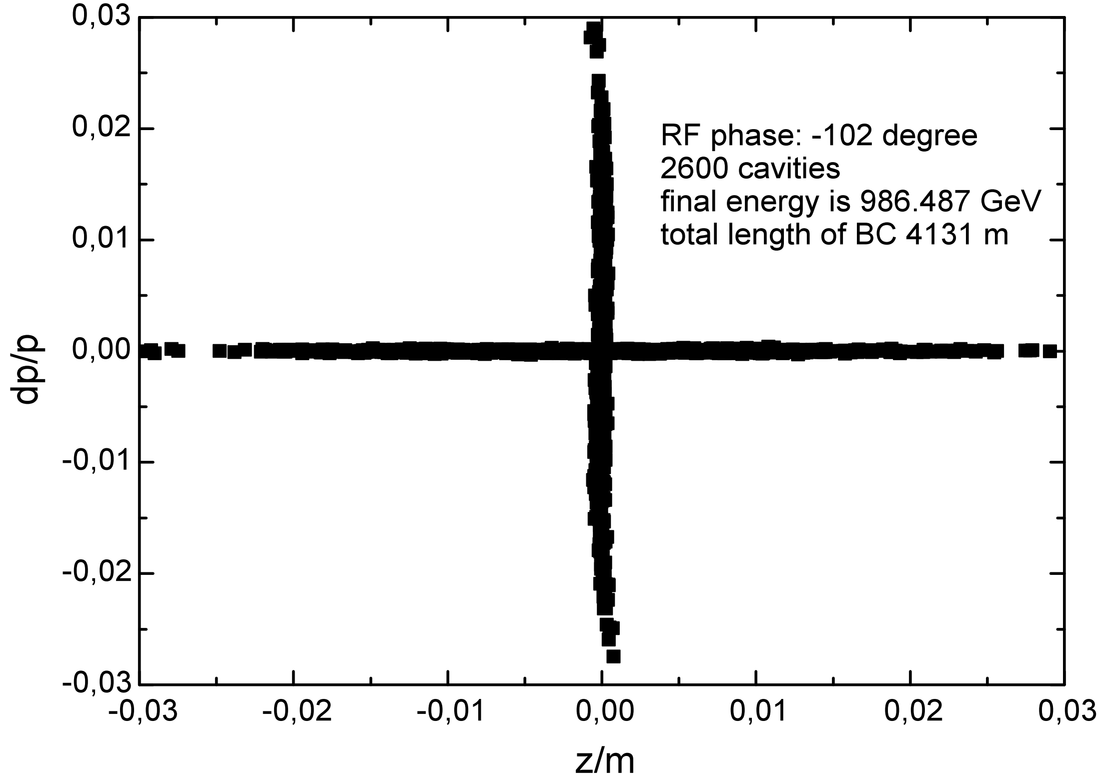
Magnetic bunch compression (BC)

- **Beam compression can be achieved:**
  (1) by introducing an energy-position correlation along the bunch with an RF section at zero-crossing of voltage
  (2) and passing beam through a region where path length is energy dependent: this is generated by bending magnets to create dispersive regions.



- **To compress a bunch longitudinally, trajectory in dispersive region must be shorter for tail of the bunch than it is for the head.**

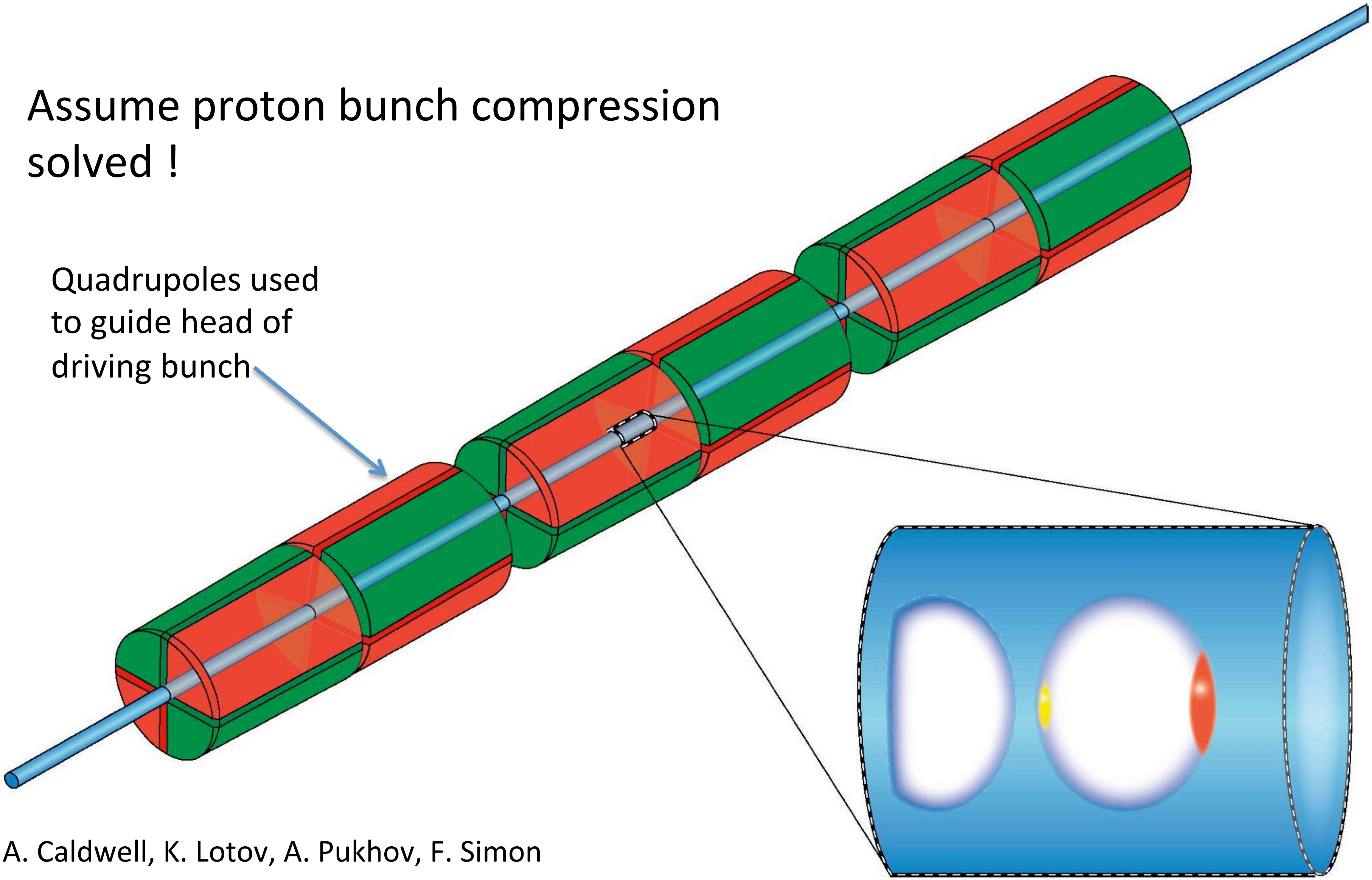
Phase space of beam



See A. Caldwell, G. Xia et al., Preliminary study of proton driven plasma wakefield acceleration, Proceedings of PAC09, May 3-8, 2009, Vancouver, Canada

Simulation study

Assume proton bunch compression solved !



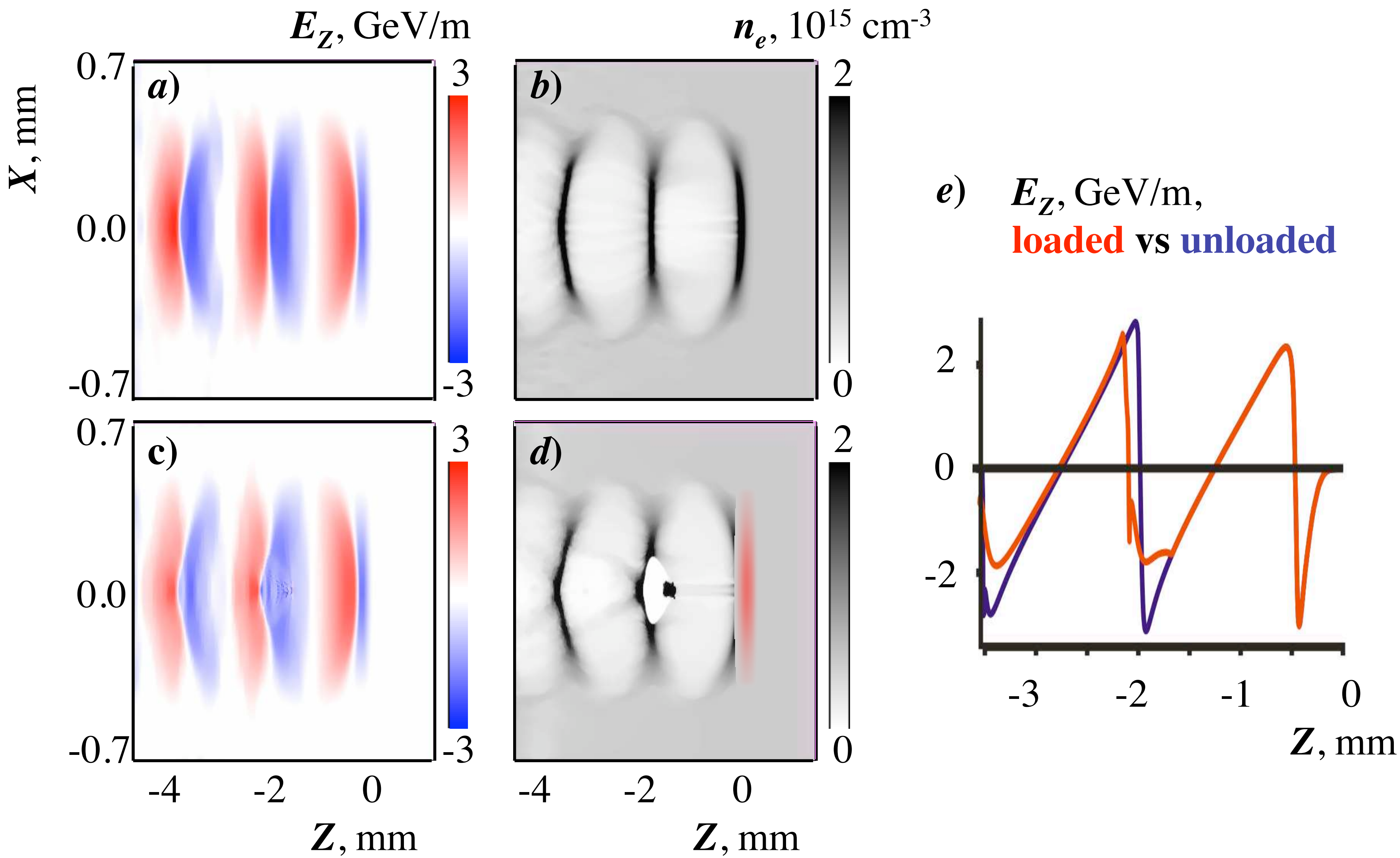
A. Caldwell, K. Lotov, A. Pukhov, F. Simon
Nature Physics ***5, 363 - 367 (2009)***

Simulation

Table 1: Table of parameters for the simulation.

Parameter	Symbol	Value	Units
Protons in Drive Bunch	N_P	10^{11}	
Proton energy	E_P	1	TeV
Initial Proton momentum spread	σ_p/p	0.1	
Initial Proton longitudinal spread	σ_Z	100	μm
Initial Proton bunch angular spread	σ_θ	0.03	mrad
Initial Proton bunch transverse size	$\sigma_{X,Y}$	0.4	mm
Electrons injected in witness bunch	N_e	$1.5 \cdot 10^{10}$	
Energy of electrons in witness bunch	E_e	10	GeV
free electron density	n_p	$6 \cdot 10^{14}$	cm^{-3}
Plasma wavelength	λ_p	1.35	mm
Magnetic field gradient		1000	T/m
Magnet length		0.7	m

Densities & Fields

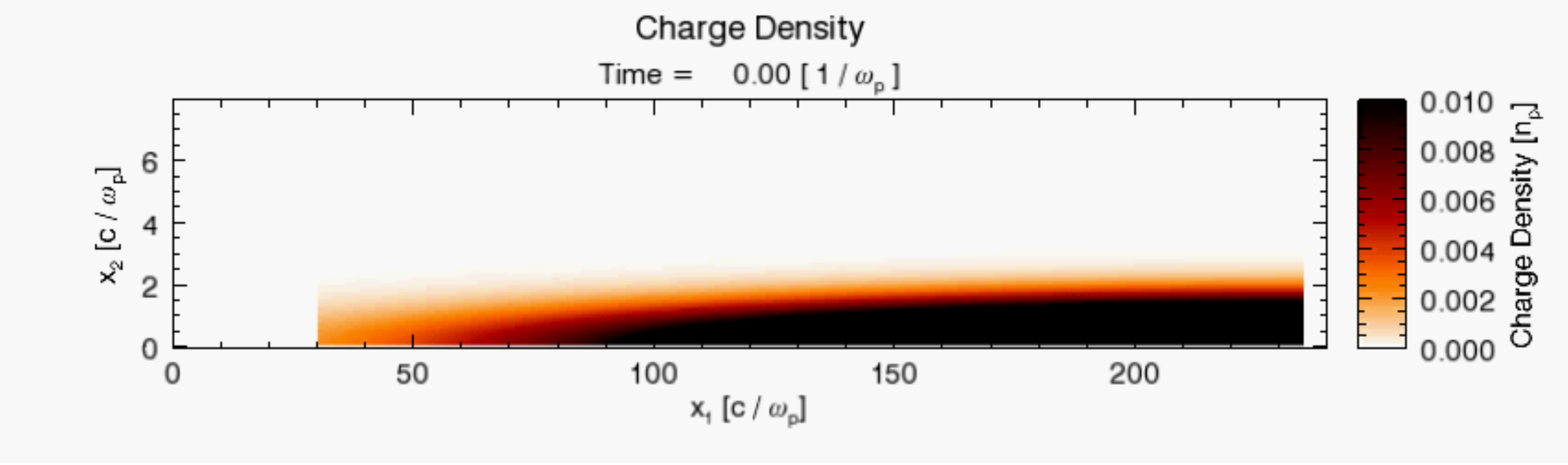


PWA via Modulated Proton Beam

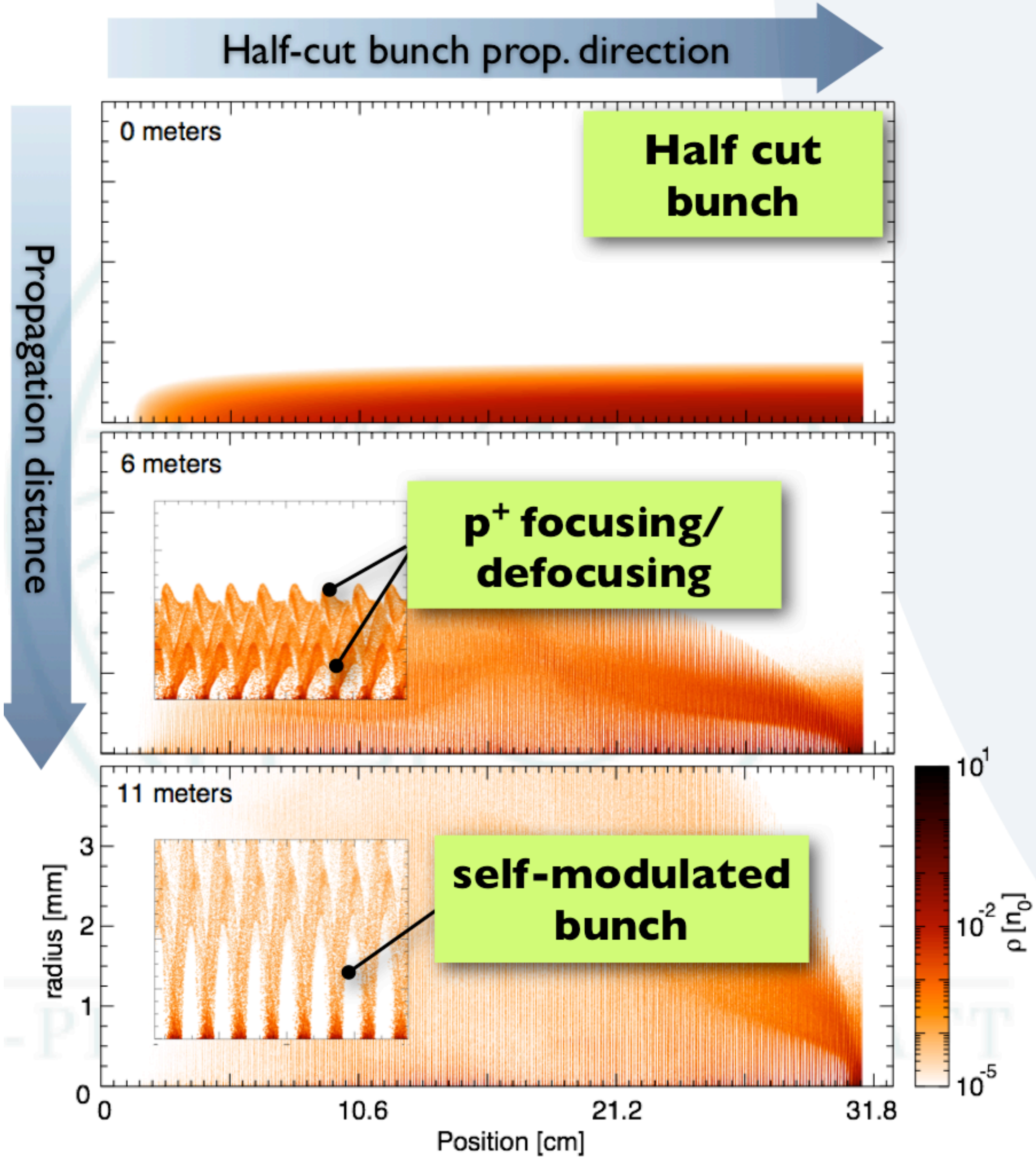
Producing short proton bunches not possible today w/o major investment. Not an option for the short term …

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)).



Courtesy Wei Lu, Tsinghua University



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

Courtesy: Jorge Vieira IST, Lisbon

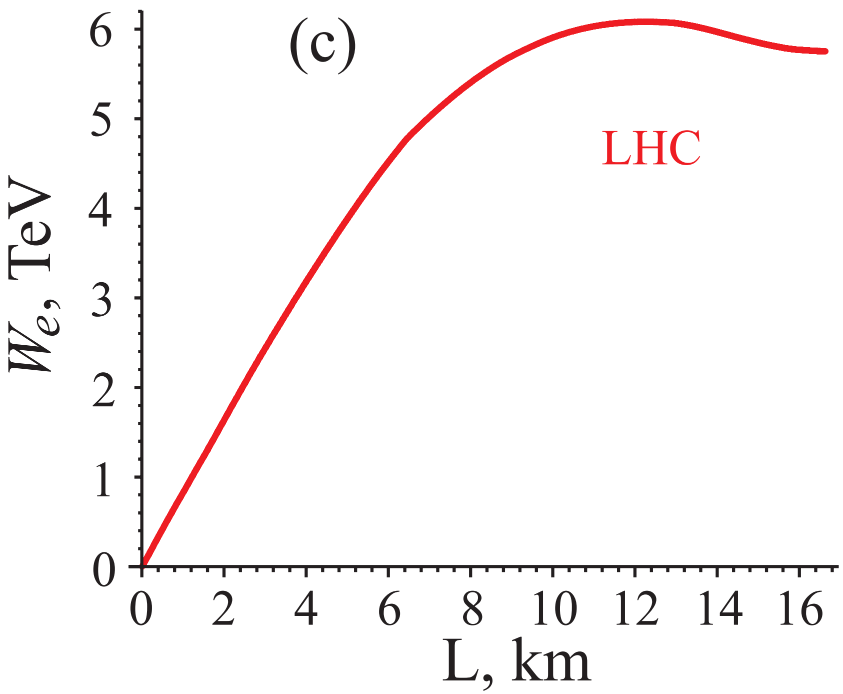
Outlook

Long term prospects for modulated proton bunch intriguing:

simulation of existing LHC bunch in plasma with trailing electrons …

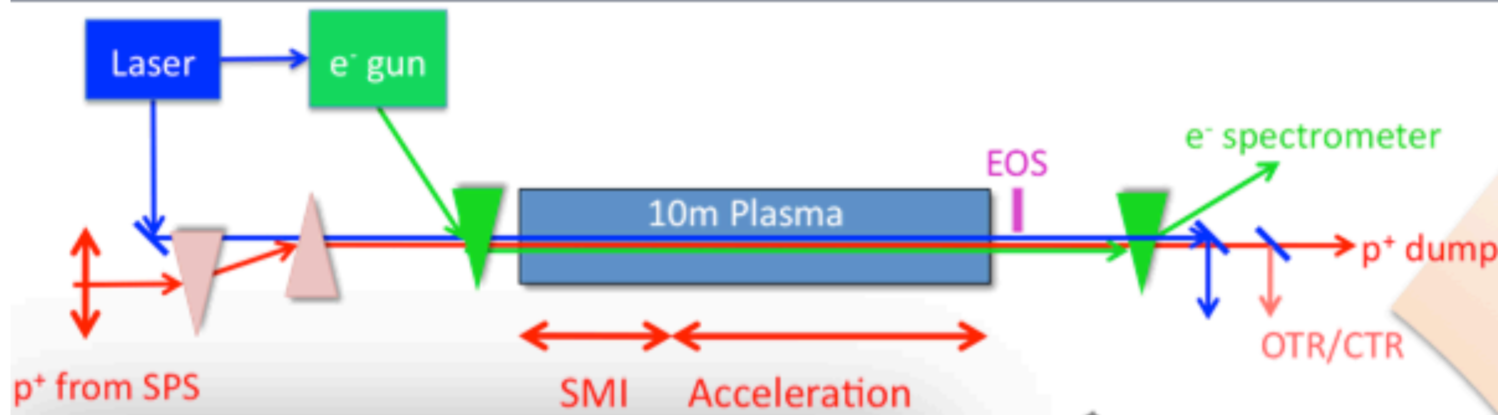
A. Caldwell, K. V. Lotov, Phys. Plasmas **18**, 13101 (2011)

Electron energy gain

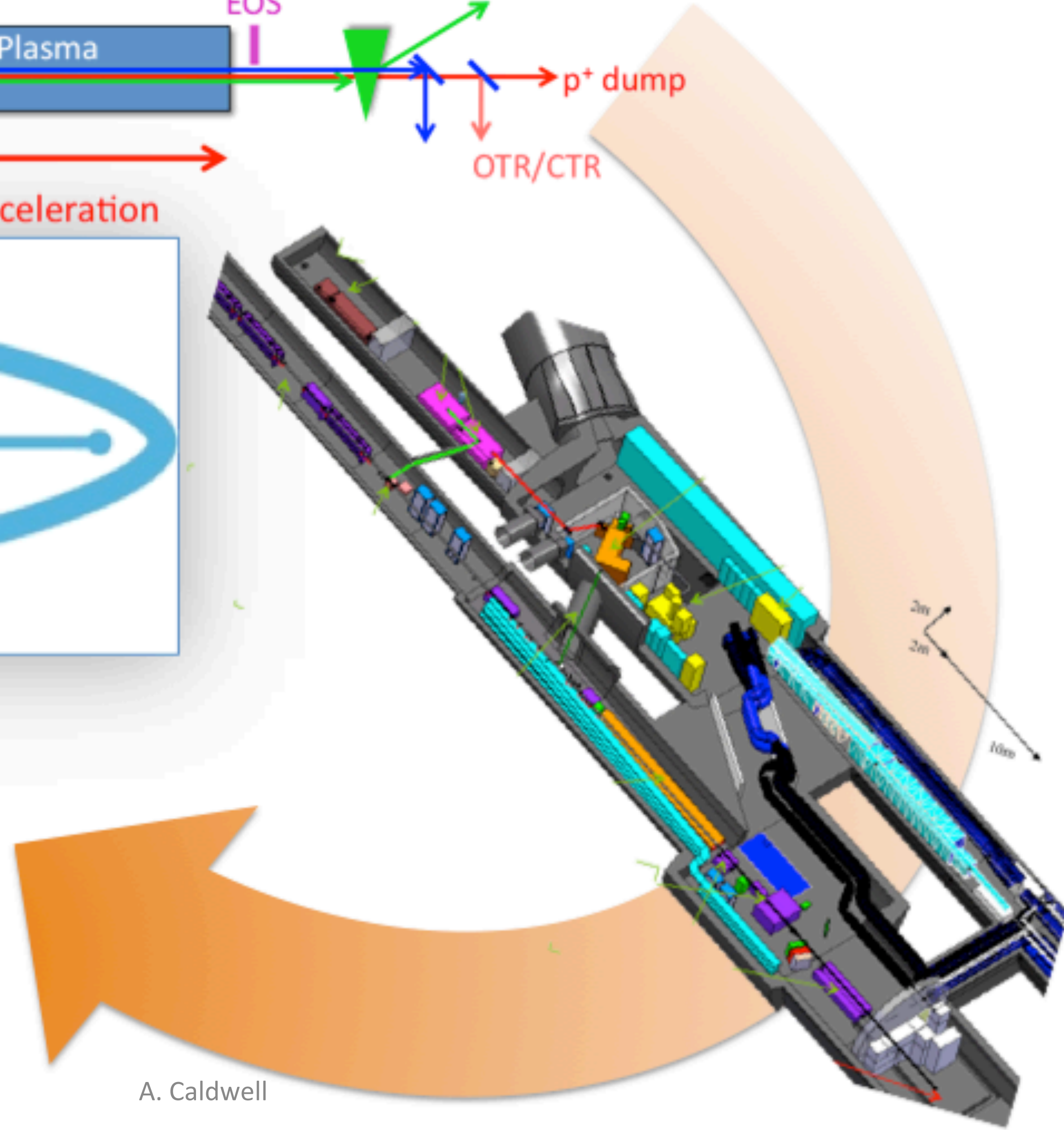


Miracle: no guiding magnetic fields necessary !

But – luminosity will be big issue !


Laser
e⁻ gun
EOS
e⁻ spectrometer
10m Plasma
p⁺ dump
OTR/CTR
p⁺ from SPS
SMI
Acceleration


Future AWAKE experimental area
(will be emptied)



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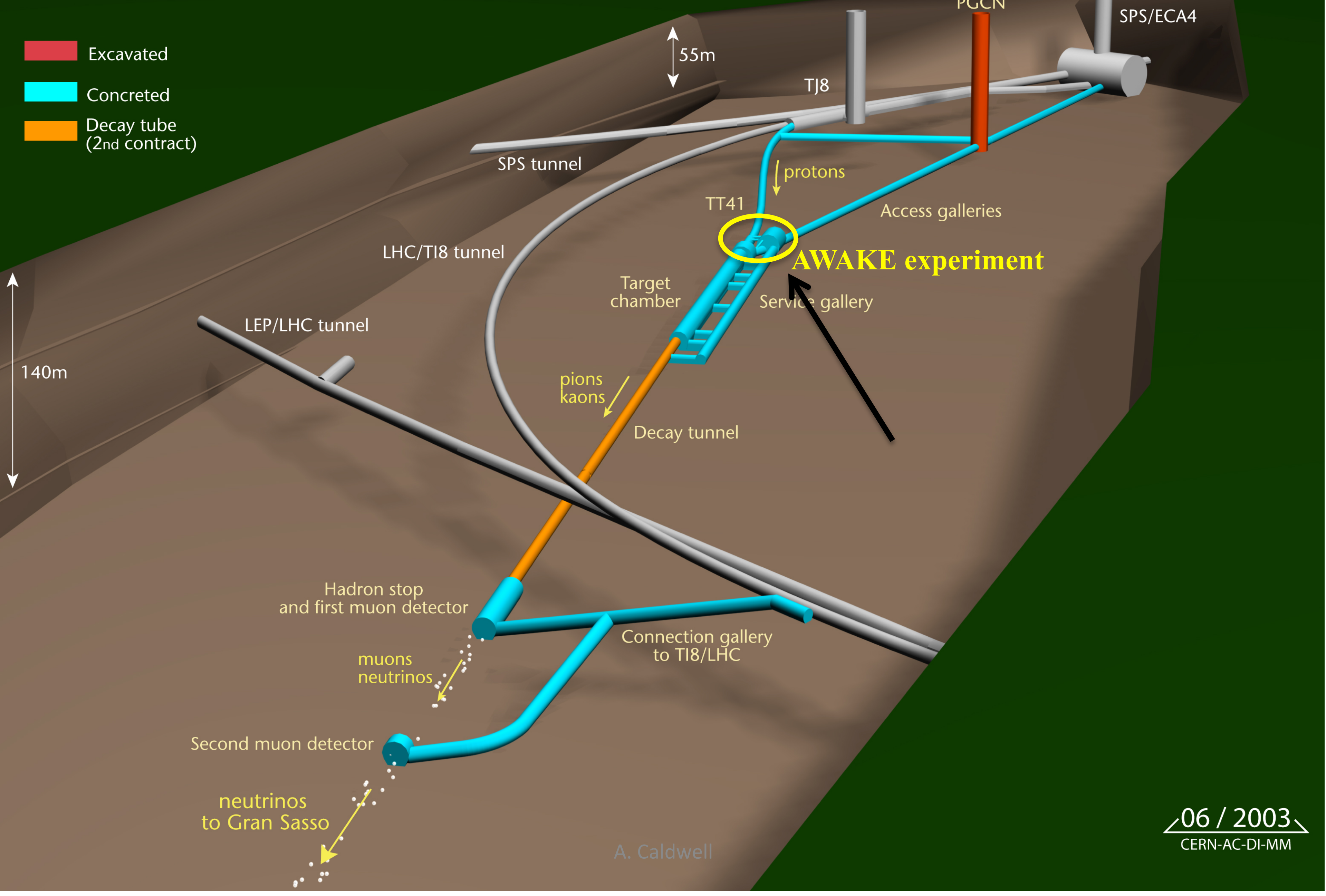
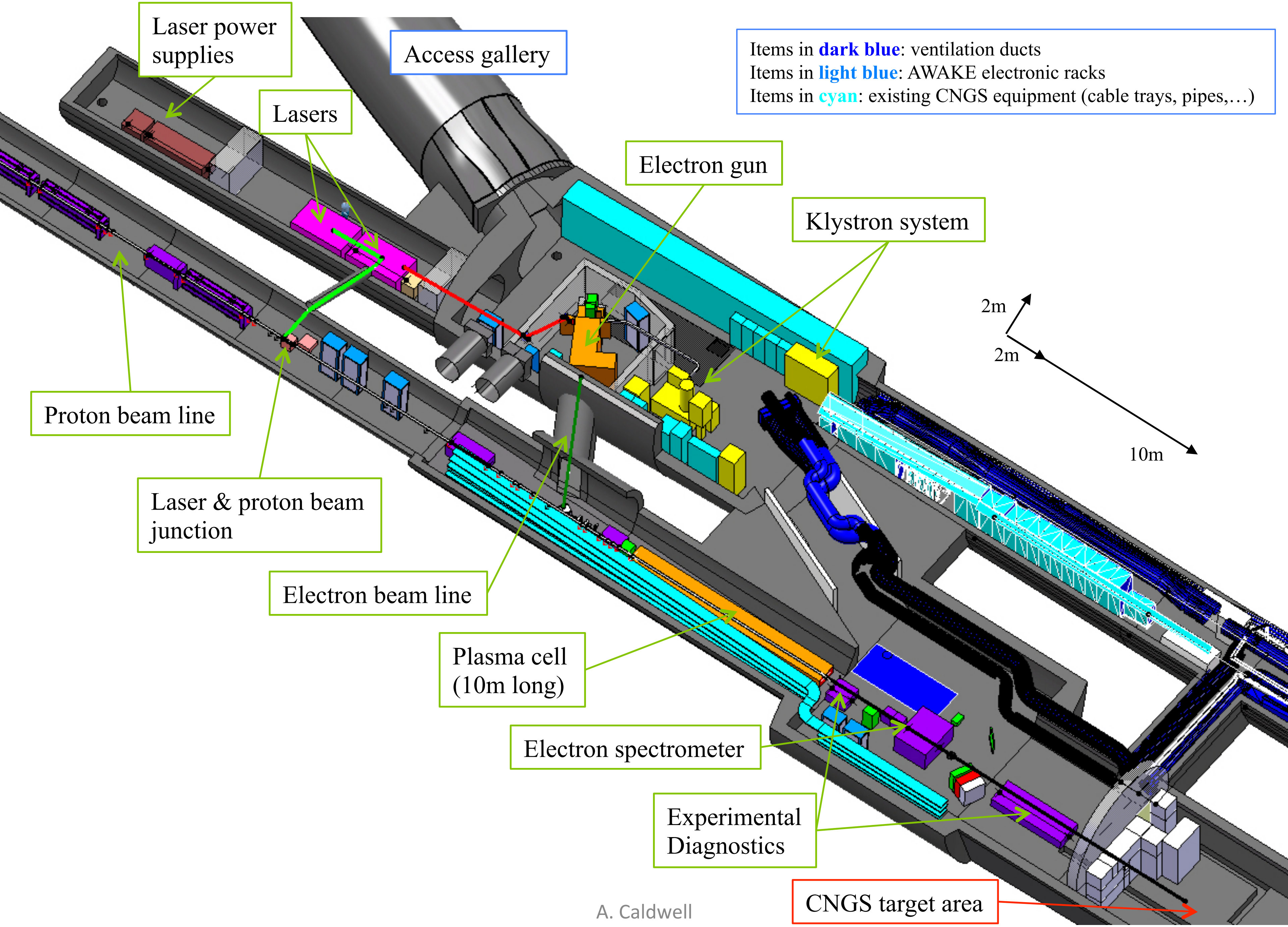
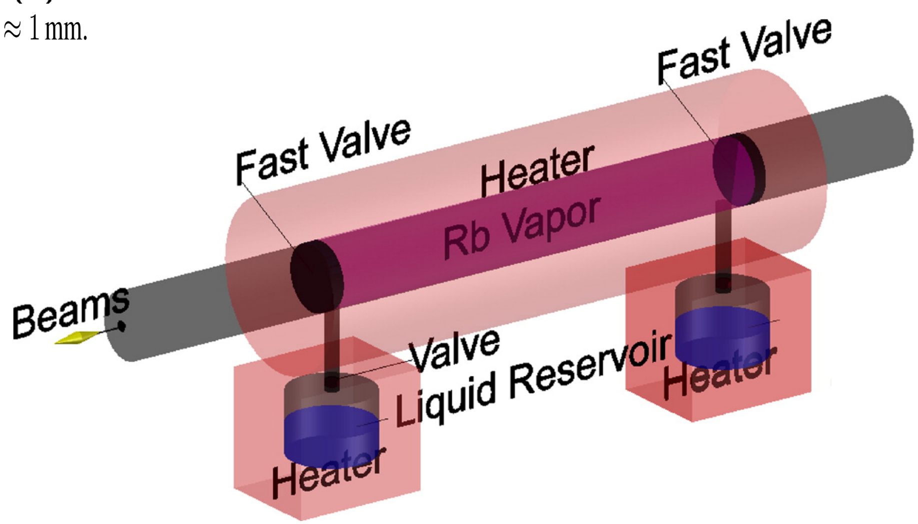
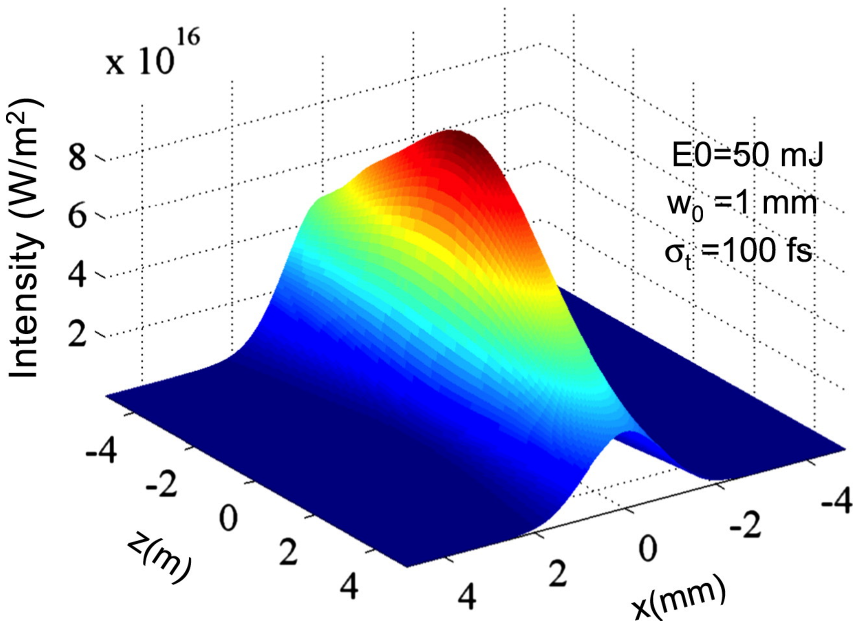
CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN




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
A. Caldwell

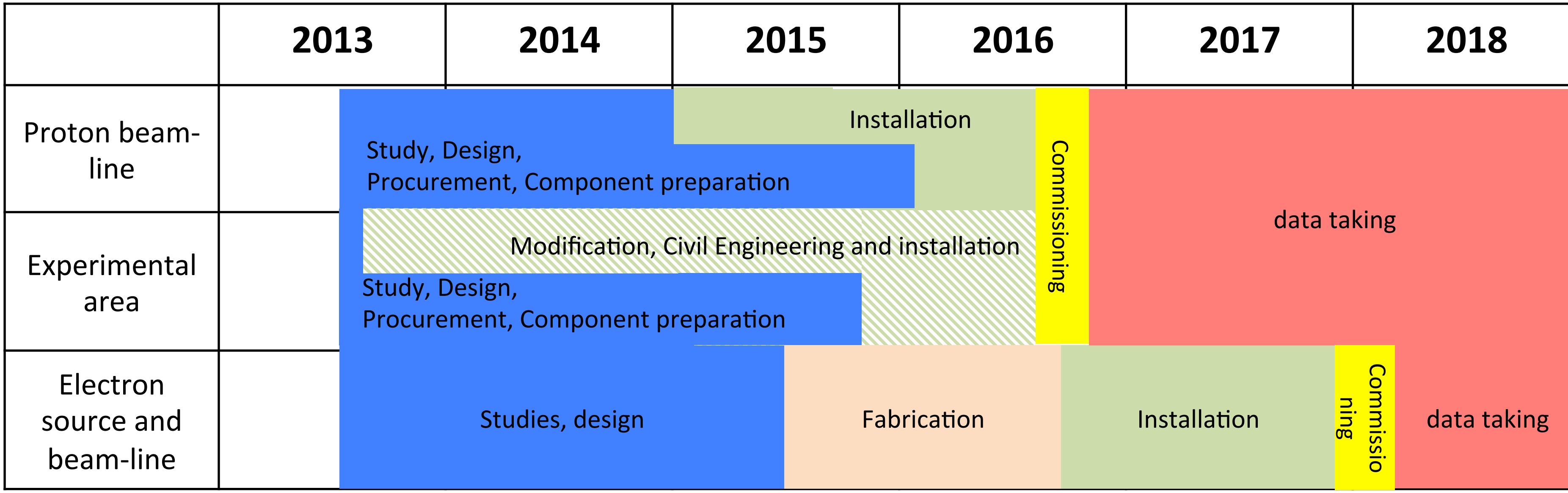
- length $L \approx 10\,\mathrm{m}$.
- radius R_p larger than approximately three proton bunch rms radii or $\approx 1\,\mathrm{mm}$.
- density n_e within the $10^{14} - 10^{15}\,\mathrm{cm}^{-3}$ range.
- density uniformity $\delta n_e / n_e$ on the order of 0.2% or better.
- reproducible density.
- gas/vapor easy to ionize.
- allow for seeding of the SMI.
- high-Z gases to avoid background plasma ion motion [25].





Few 50 mJ, few TW laser required to ionize the vapor

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. Caldwell

A possible future

electron-positron collider based on proton driven plasma wakefield acceleration

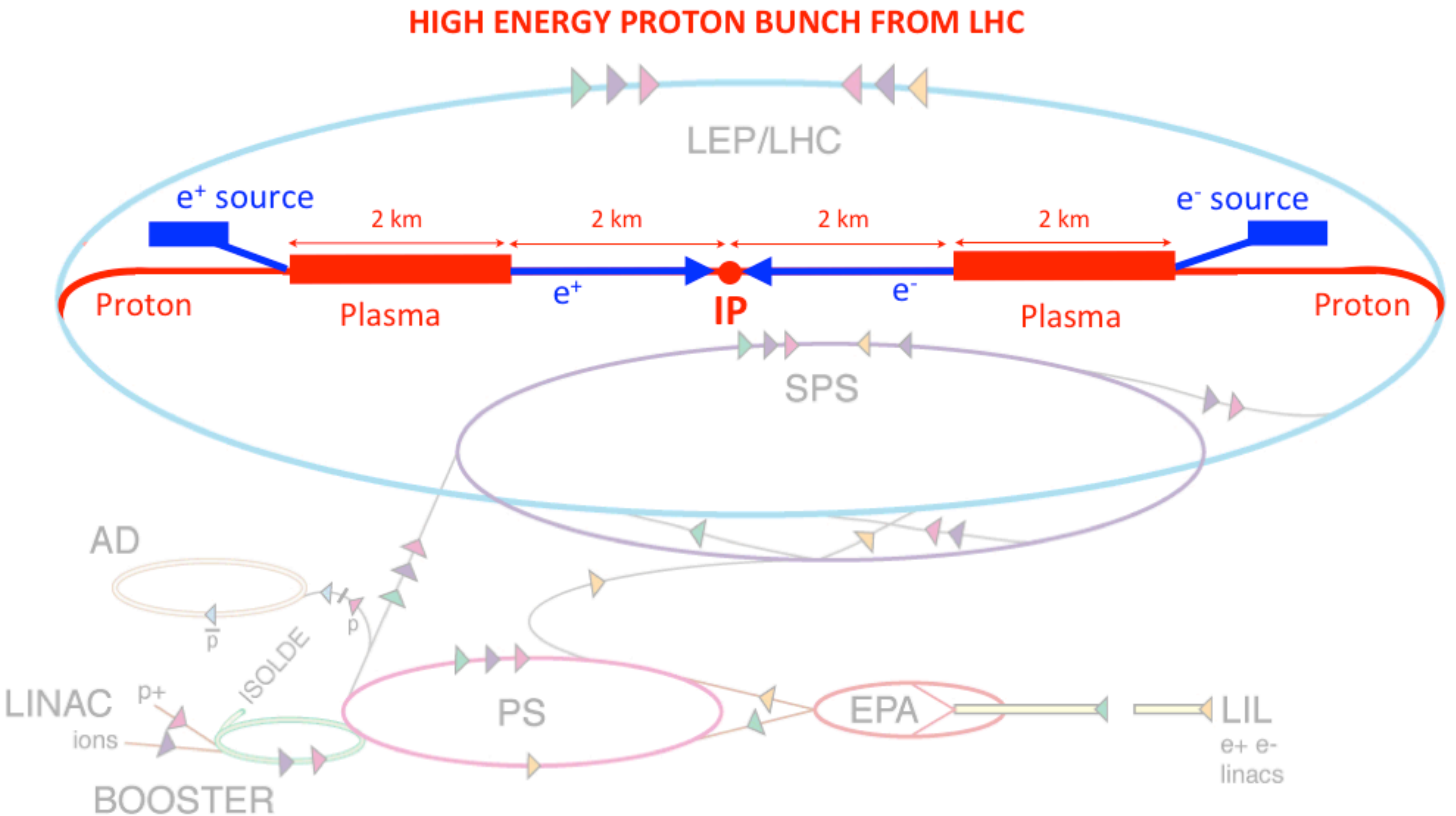
and/or

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 ➟ $3 \times 10^{31}\ cm^{-2}\ s^{-1}$

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

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

The *Luminosity* Issue

Collider luminosity ($cm^{-2}\,s^{-1}$) is approximately given by

$$L = \frac{n_b N^2 f_{rep}}{A} H_D$$

where:

N_b = bunches / train
N = particles per bunch
f_{rep} = repetition frequency
A = beam cross-section at IP
H_D = beam-beam enhancement factor

For *Gaussian* beam distribution:

$$L = \frac{n_b N^2 f_{rep}}{4\pi \sigma_x \sigma_y} H_D$$