CERN Beam Line Experiments: From CNGS to AWAKE

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Austrian Teachers Programme

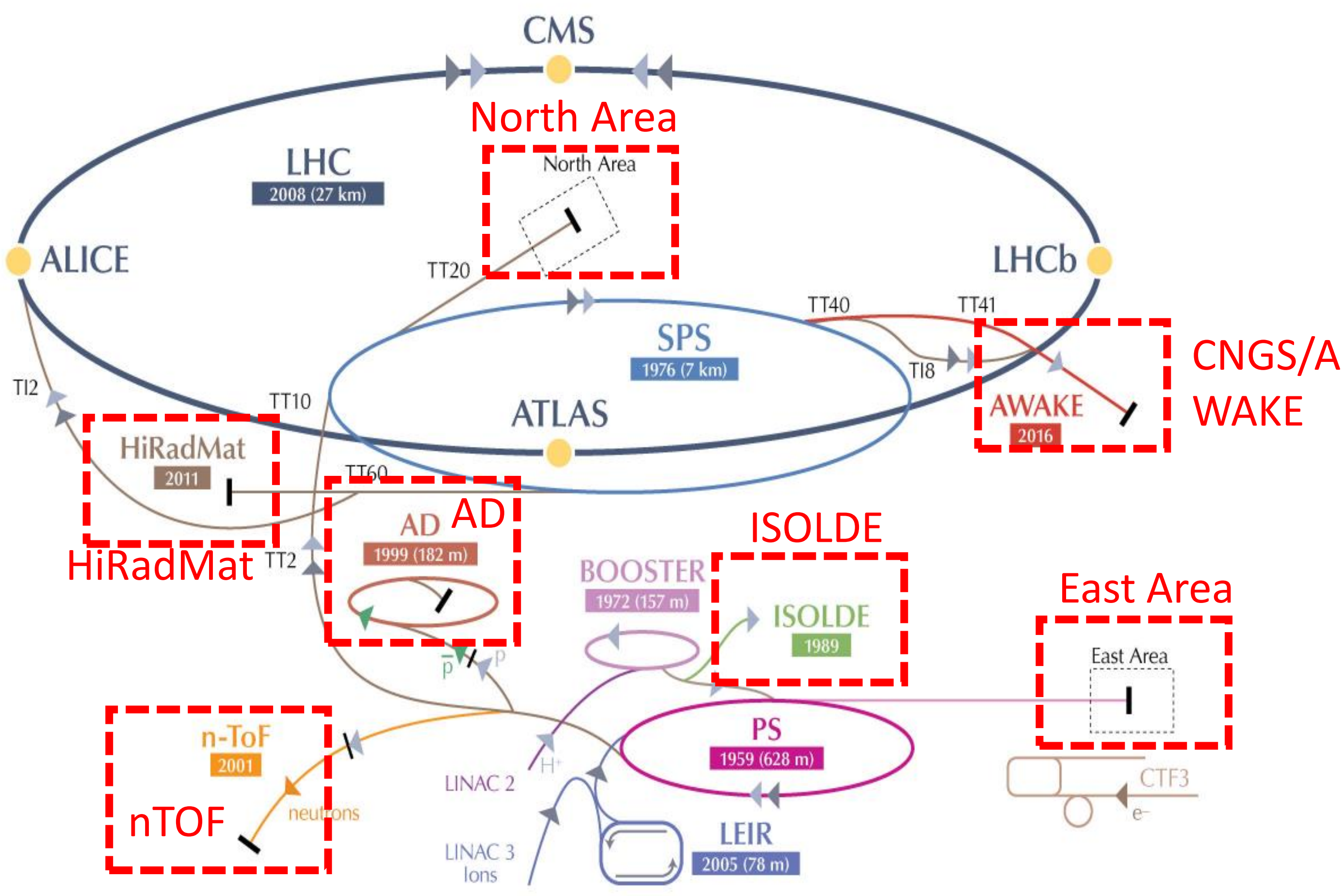
15 – 20 November 2015

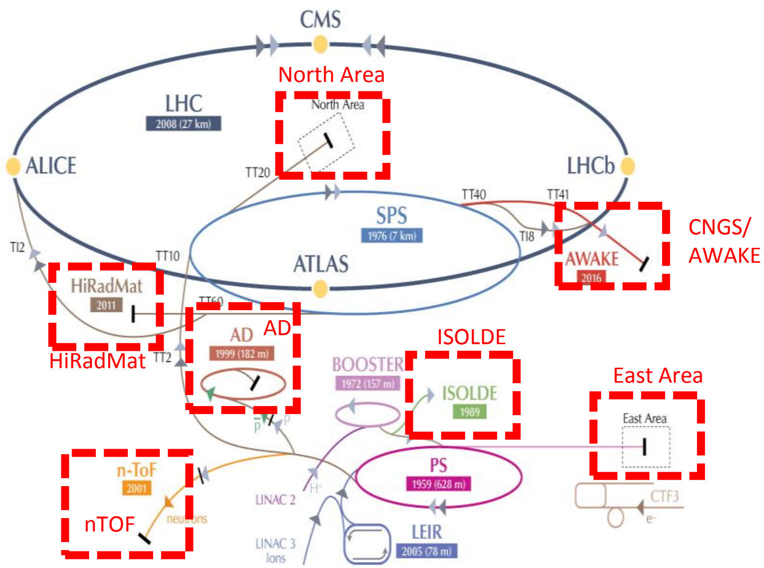
CERN Accelerator Complex

2010:

5.3 10^{15} protons to LHC

1.37 10^{20} protons to CERN's Non-LHC Experiments and Test Facilities





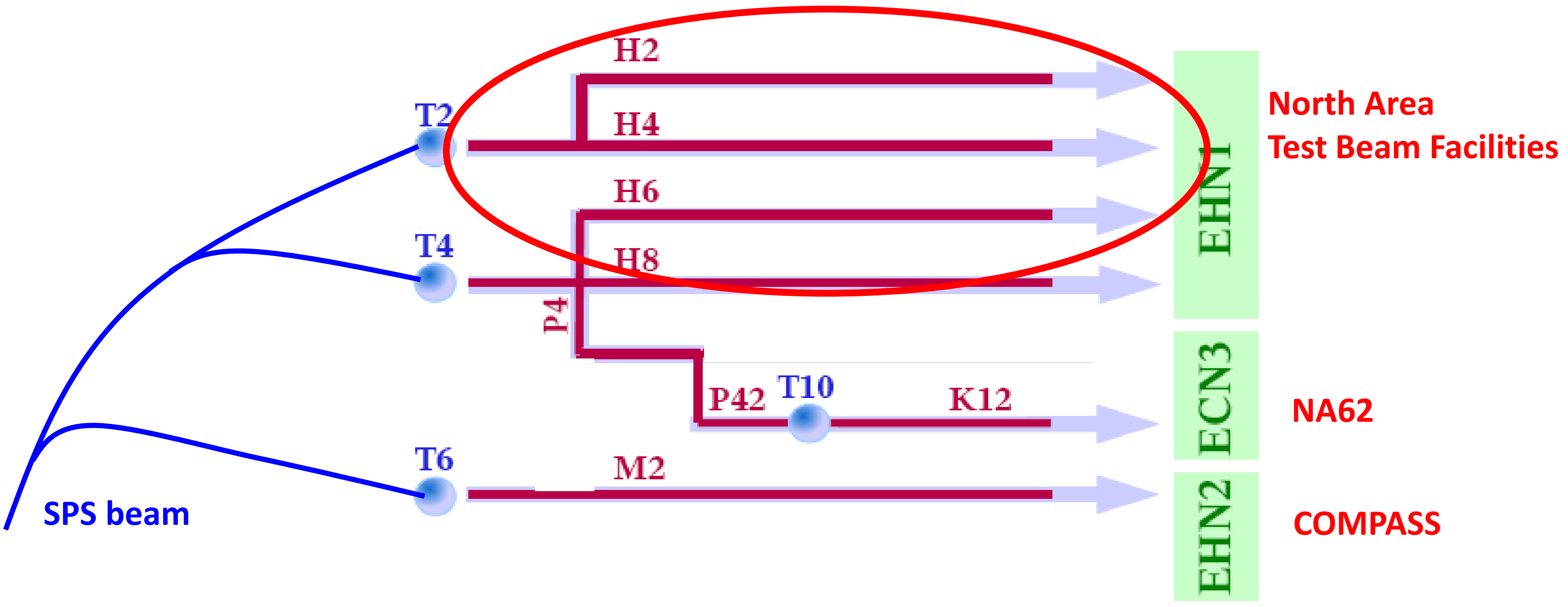
CERN Accelerator Complex

East Area	Test-beams	Detector, electronics, radiation, … tests
	CLOUD	study possible link between cosmic rays and cloud formation
	DIRAC	Study the decay of dimesons, gain insight in strong force
ISOLDE		Produce range of isotopes for research
AD		Anti-matter experiments
HiRadMat		User facility to test high-intensity beam onto material
North Area	Test-beams	Detector, electronics, radiation, … tests
	COMPASS	Study how elementary quarks and gluons work together to give particles we observe
	NA61	Measurement of strong-interaction (quark-gluon plasma), neutrino beam flux
	NA62	Measurement of very rare kaon decay
CNGS		CERN Neutrinos to Gran Sasso, measure neutrino oscillation
AWAKE		Demonstrate potential of Proton Driven Plasma Wakefield Acceleration Experiment

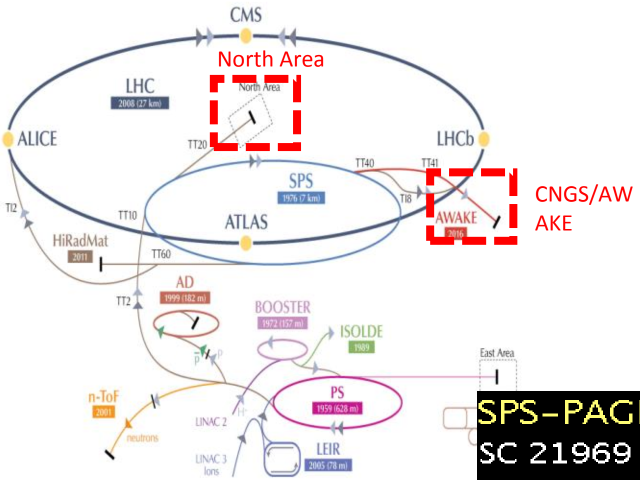
The North Experimental Areas at the SPS

- The SPS proton beam (400/450 GeV/c) slowly extracted to North Area
- Directed towards the three North Area primary targets T2, T4 and T6
- From the primary targets:
  - T2 → H2 and H4 beam lines
  - T4 → H6 and H8 beam lines
    and P42/K12 beam line (NA62)
  - T6 → M2 beam line (NA58/COMPASS)

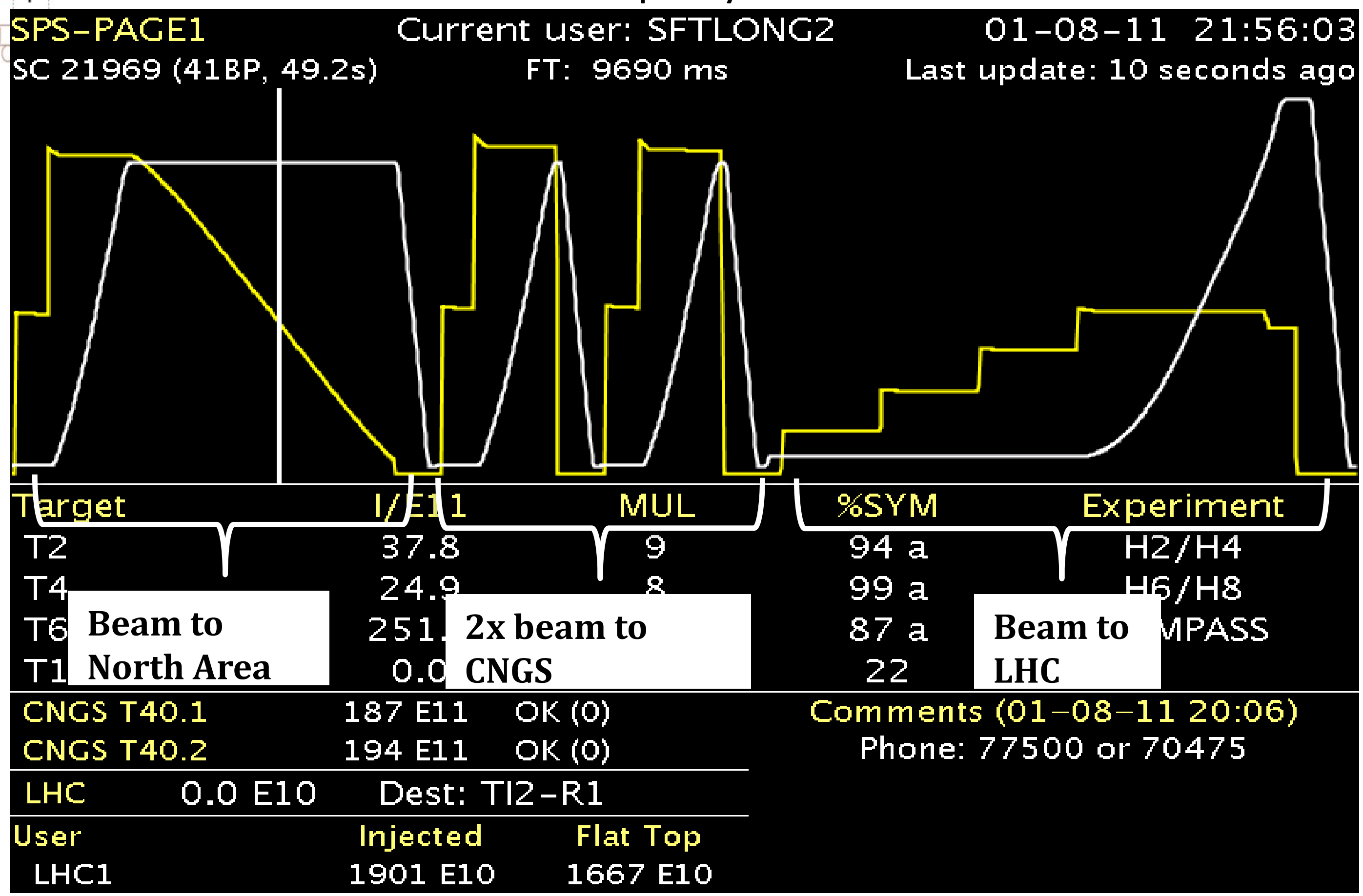
Particle momentum range:
10-400 GeV/c



How Do We Send the Beam to the Beam Line Experiments?



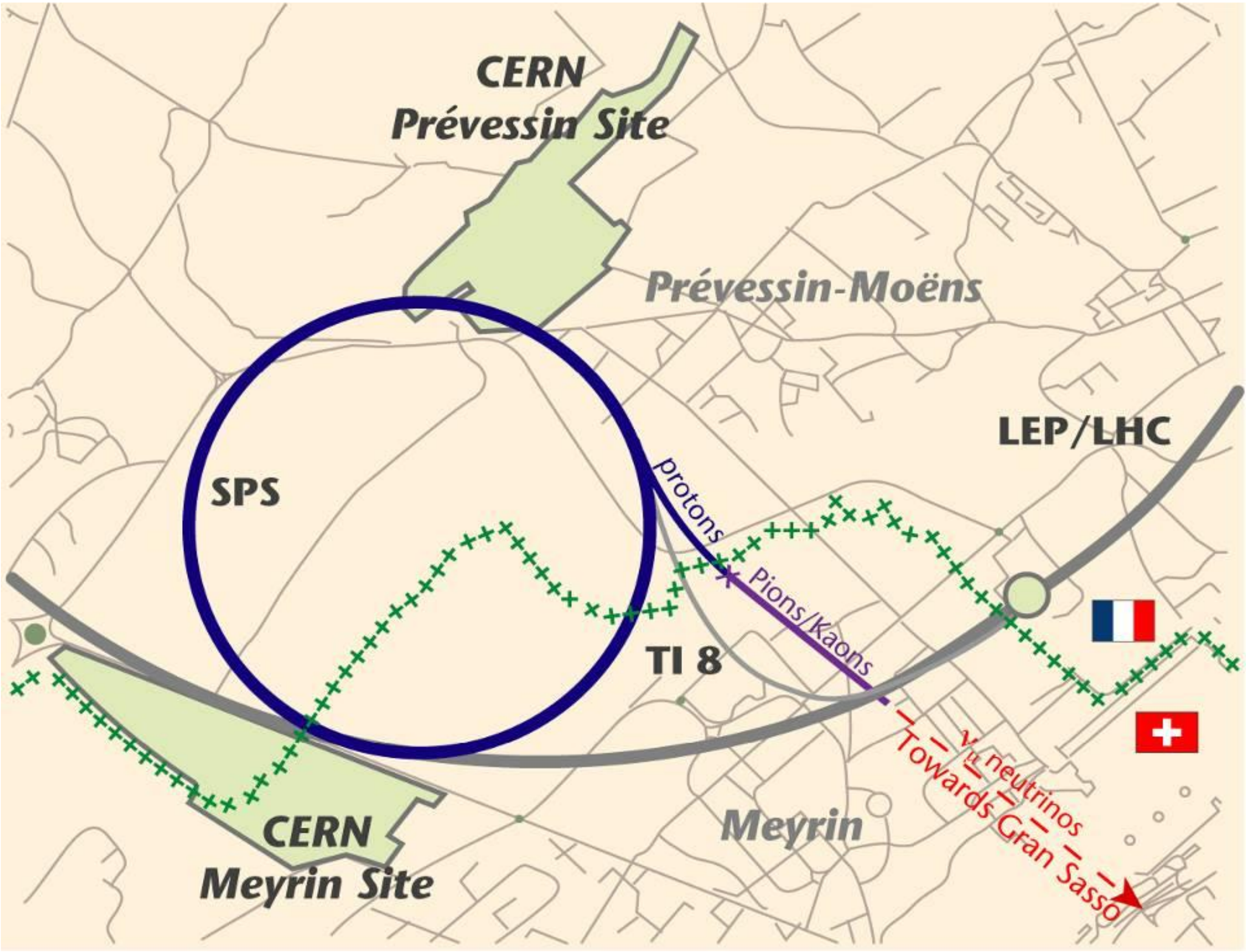
1 SPS Supercycle



CNGS, CERN Neutrinos to Gran Sasso

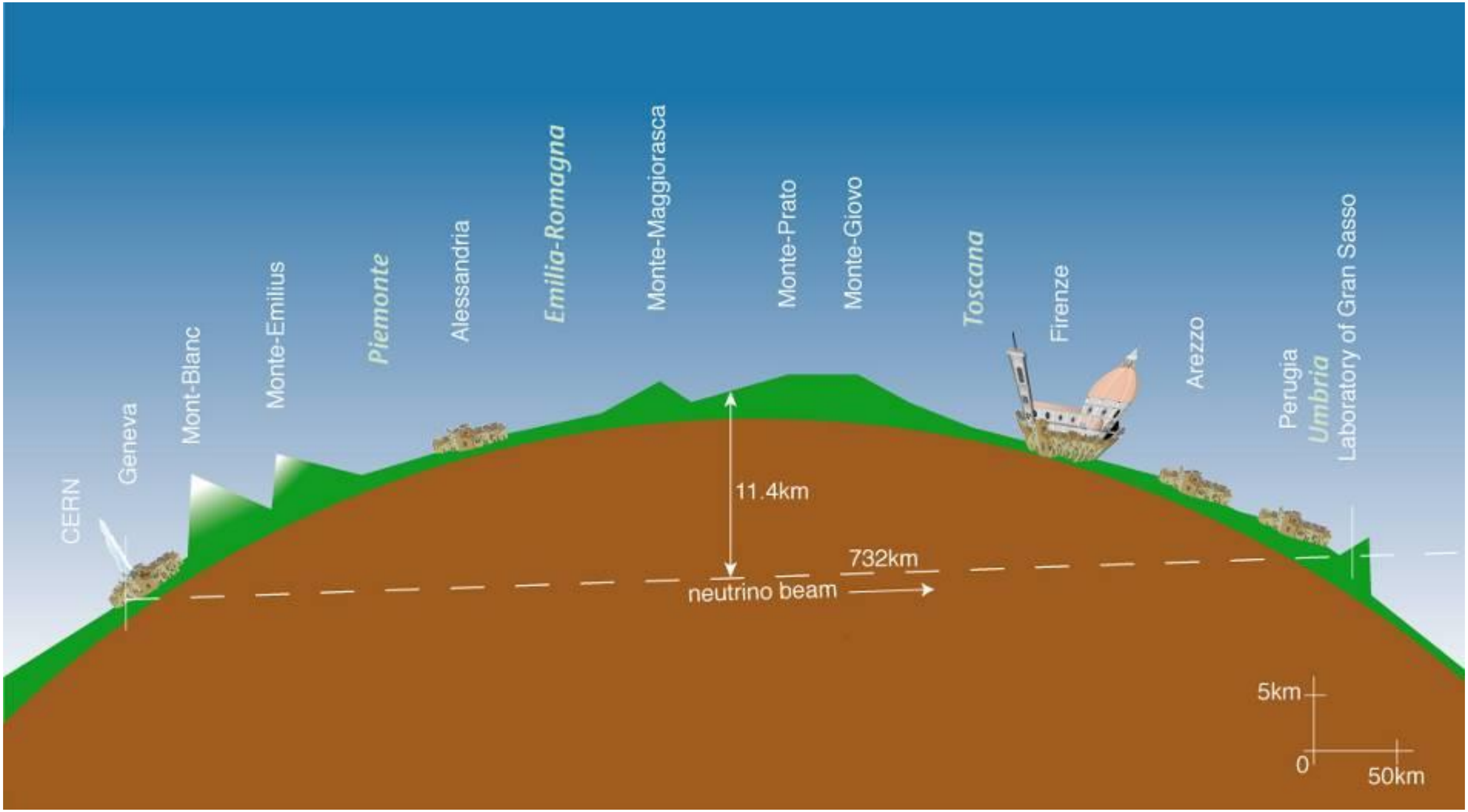
CNGS, CERN Neutrinos to Gran Sasso

2006 – 2012

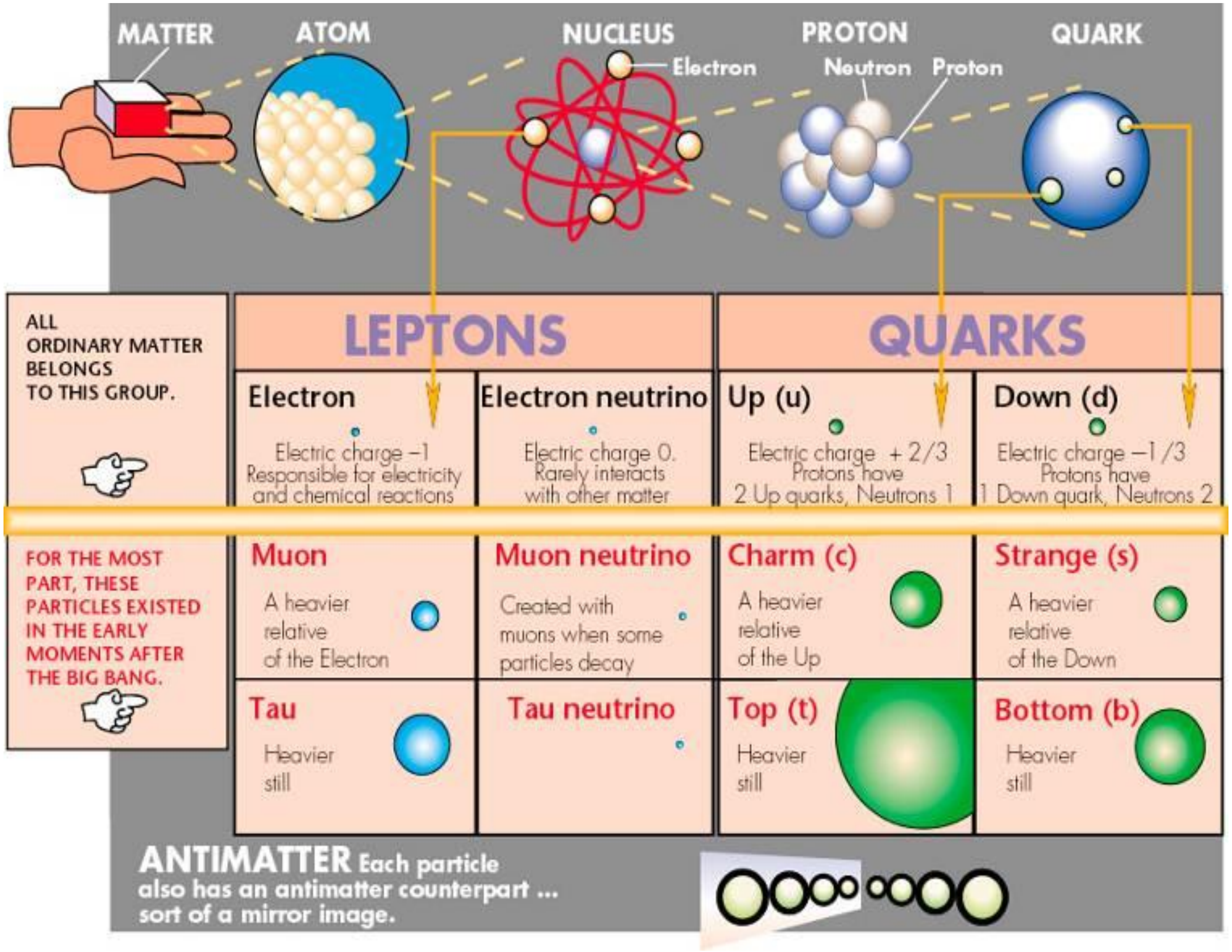


CERN Neutrinos to Gran Sasso

- A long base-line neutrino beam facility (732km)
- Send neutrino beam produced at CERN to Gran Sasso



Standard Model



What are Neutrinos (ν) ?

- ➔ elementary particles
- ➔ come in three flavors (LEP)
- ➔ electric charge: zero !
- ➔ mass: very small zero?
- ➔ interaction with matter: "very weak"

Leptons

particle	electric charge
e	-1
ν_e	0
μ	-1
ν_μ	0
τ	-1
ν_τ	0

+ antiparticles

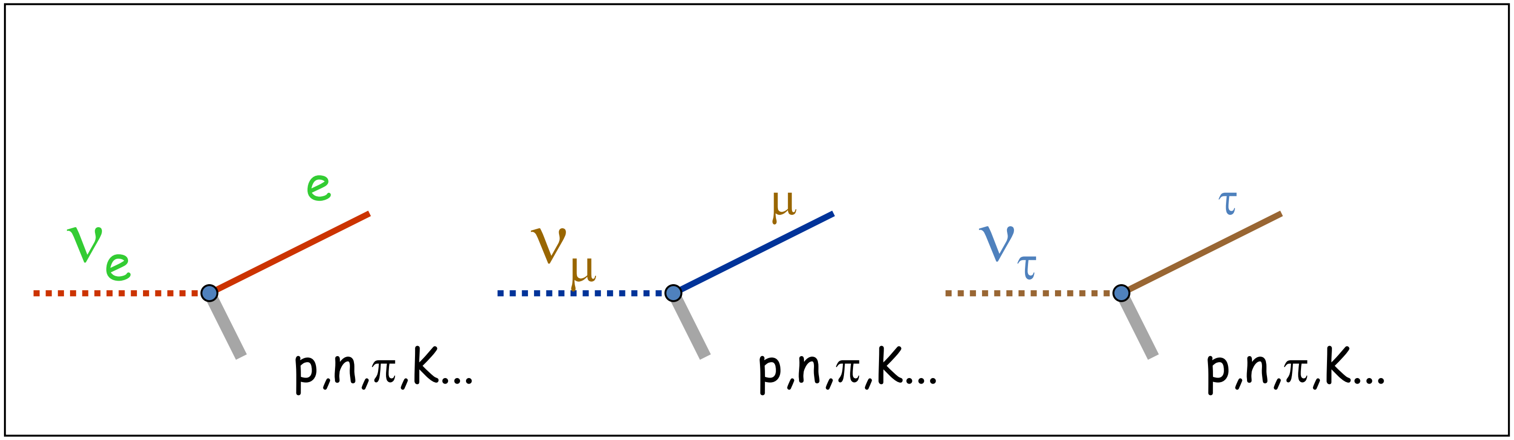
Neutrinos

Weakly interacting leptons ν_e, ν_μ, ν_τ, no charge

- Solar Neutrinos:
  - $6 \cdot 10^{14}$ neutrinos/s/m^2
    - → Every 100 years 1 neutrino interacts in human body
    - → 10^{16} meter lead to stop half of these neutrinos
- Natural radioactivity from earth:
  - $6 \cdot 10^{6}$ neutrinos/s/cm^2.
- ^{40}K in our body:
  - $3.4 \cdot 10^{8}$ neutrinos/day
- Cosmic neutrinos:
  - 330 neutrinos/cm^3
- CNGS
  - Send ~10^{17} neutrinos/day to Gran Sasso

How do we detect Neutrinos

neutrinos interact VERY rarely with matter - when they do, they often produce a lepton of their 'own flavour':



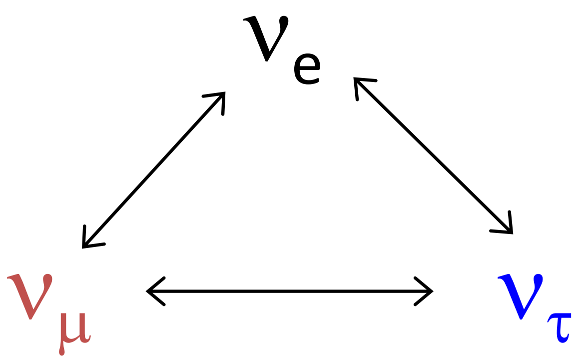
NOTE: a minimum amount of energy is needed (to create the mass of the lepton):

m_e = 0.5 MeV, - m_μ = 106 MeV - m_τ = 1770 MeV

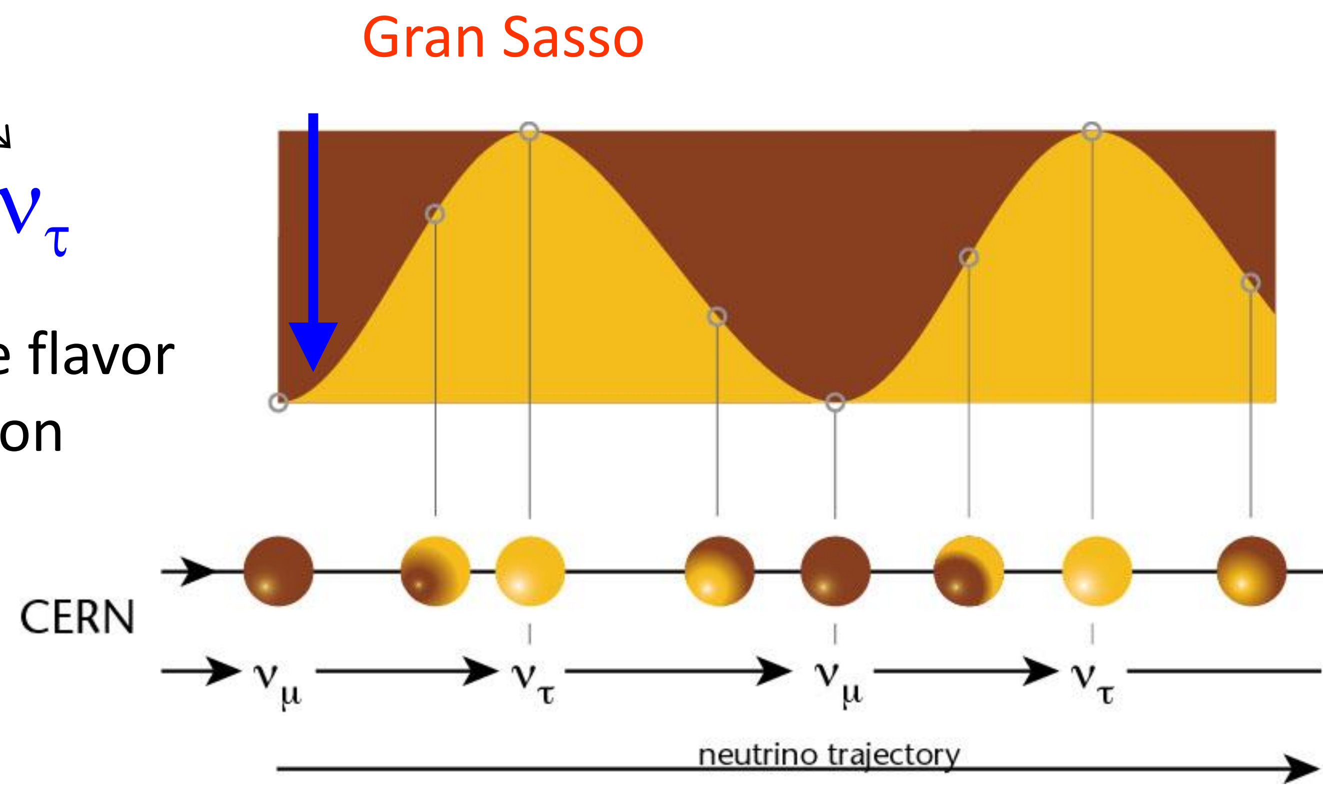
The higher the neutrino energy, the more likely the interaction !

Neutrinos

If neutrinos have mass:



➔Neutrinos change flavor
➔Neutrino oscillation



Neutrino Parameter Status: July 2008 Review of Particle Physics

Direct measurement of neutrino masses: still compatible with Zero:

$\nu_e < 2\text{eV}$ $\nu_\mu < 0.19\text{MeV}$ $\nu_\tau < 18.2\text{MeV}$

If flavor eigenstates and mass eigenstates are different (mixing) and if masses are different → neutrino oscillation

Mass states: $|\nu_1\rangle \quad |\nu_2\rangle \quad |\nu_3\rangle$ Flavor states: $|\nu_e\rangle \quad |\nu_\mu\rangle \quad |\nu_\tau\rangle$

$$m_1, m_2, m_3 \qquad \Delta m_{12} = m_2 - m_1, \quad \Delta m_{23} = m_3 - m_2$$

Mixing of the three neutrinos: unitary 3x3 matrix → 4 parameters like the CKM matrix for Quarks. CP violating phase not yet accessible → currently 3 mixing angles θ.

$$|\nu_\alpha\rangle = \sum_{n=1}^{3} U^*_{\alpha i} |\nu_i\rangle \quad \sim \quad \begin{pmatrix} |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta_{23} & \sin\theta_{23} \\ -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

$$P_{\mu\to\tau} = \sin^2(2\theta_{23}) \sin^2\left(\frac{\Delta m_{23}^2 L}{4E}\right)$$

$\Delta m^2_{21} = 8 \pm 0.3 \times 10^{-5}\ \text{eV}^2$ $\Delta m_{21} = 9 \pm 0.17$ meV solar and reactor Neutrinos

$\Delta m^2_{32} = 2.5 \pm 0.5 \times 10^{-3}\ \text{eV}^2$ $\Delta m_{32} = 50 \pm 5$ meV Atmospheric and long Baseline

$\sin^2 2\theta_{21} = 0.86+0.03-0.04$ → $\theta_{21}=34-1.6+1.3$ degrees

$\sin^2 2\theta_{23} > 0.93$ → $\theta_{23}=35.3$ degrees compatible with max. mixing $\theta=45$ degrees

$\sin^2 2\theta_{13} < 0.19$ → $\theta_{13} < 13$ degrees compatible with min. mixing $\theta=0$ degrees

CNGS Project

CNGS (CERN Neutrino Gran Sasso)

- A long base-line neutrino beam facility (732km)
- send ν_μ beam produced at CERN
- detect ν_τ appearance in OPERA experiment at Gran Sasso

2006 – 2012

➔ direct proof of ν_μ - ν_τ oscillation (appearance experiment)

CERN Neutrinos to Gran Sasso

Beam Delivery:

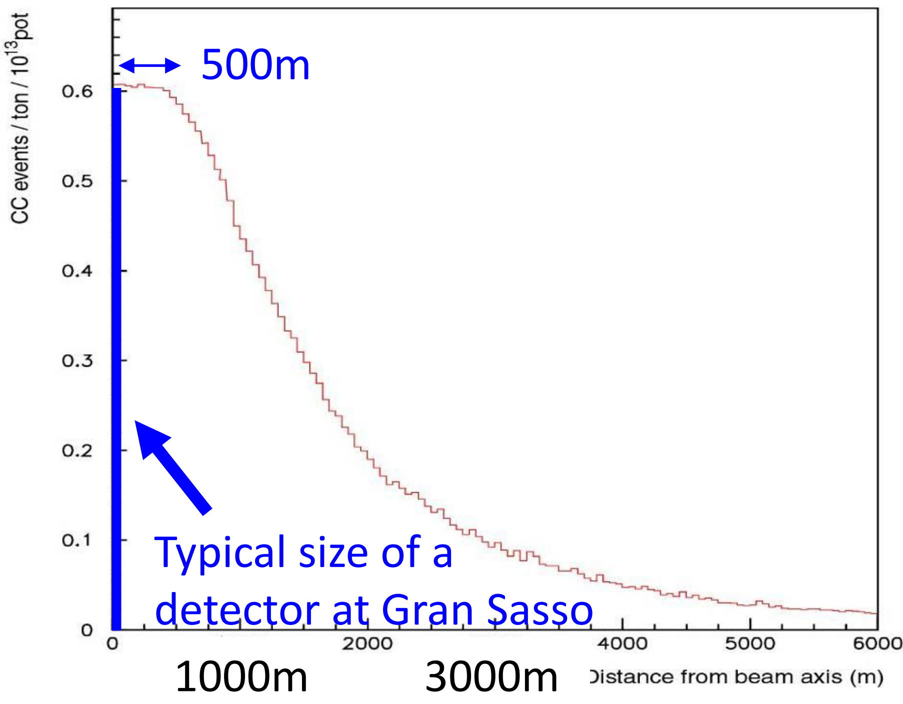
→ **$2.2 \cdot 10^{17}$ protons on target** /day

→ **~10^{17} ν_μ /day**

→ **~10^{11} ν_μ /day** at detector in Gran Sasso

→ **3600 ν_μ interactions/year** in OPERA
(charged current interactions)

→ **2-3 ν_τ interactions detected/year** in OPERA



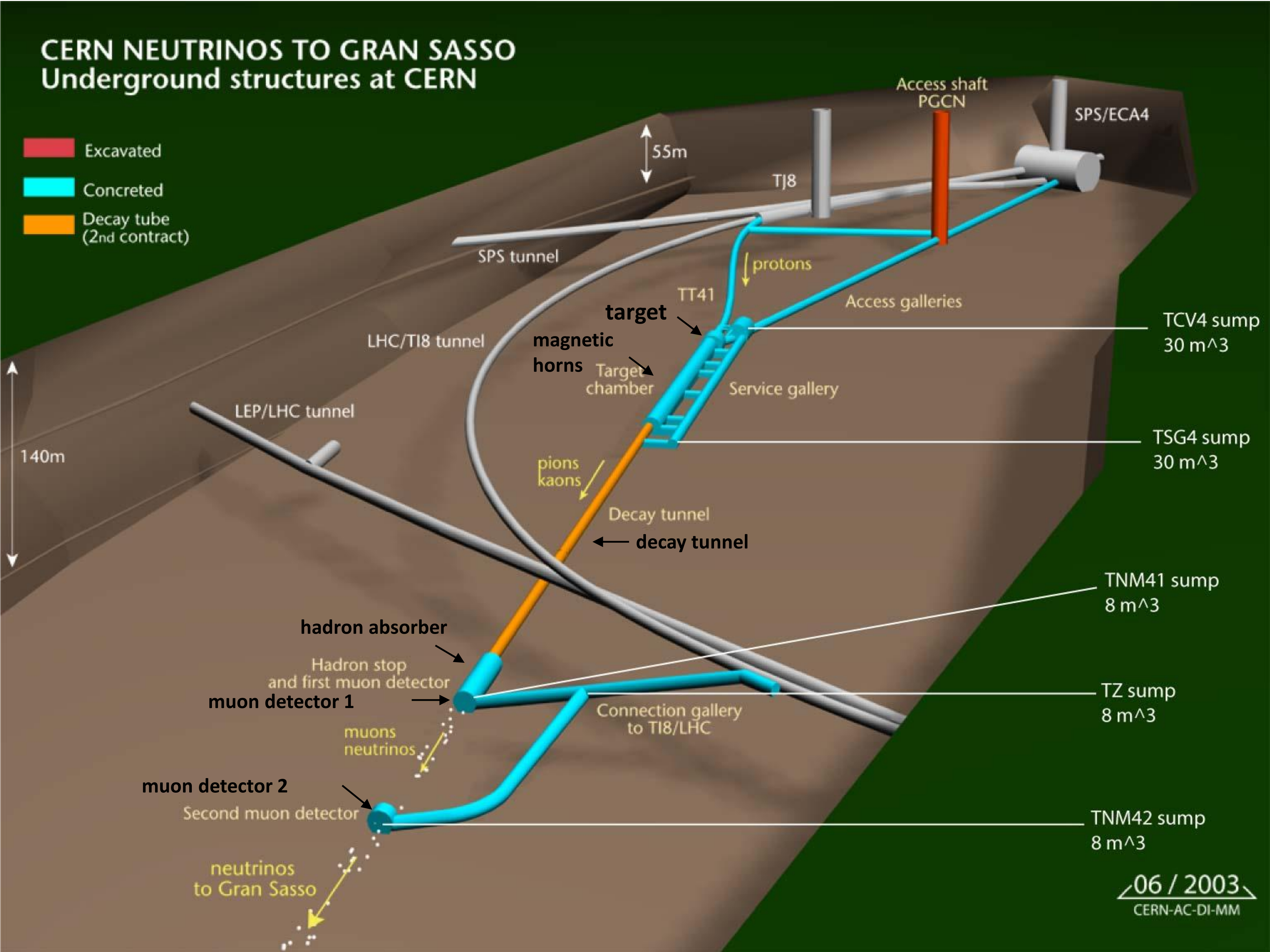
Delivered (2006-2012) **$18.24 \cdot 10^{19}$ protons on target**
(200 days/year, nominal intensity)

Status June 2015: **5 tau-neutrinos** detected

Neutrino Production

- Protons extracted from SPS
- Directed towards target
- Production of kaon, pions
- Focused with focusing magnets (horn/reflector) direction Gran Sasso
- Kaons, pions decay in decay tunnel into muons and muon-neutrinos
- Only neutrinos reach Gran Sasso

$$p + C \rightarrow \text{(interactions)} \rightarrow \pi^+,\ K^+ \rightarrow \text{(decay in flight)} \rightarrow \mu^+ + \nu_\mu$$

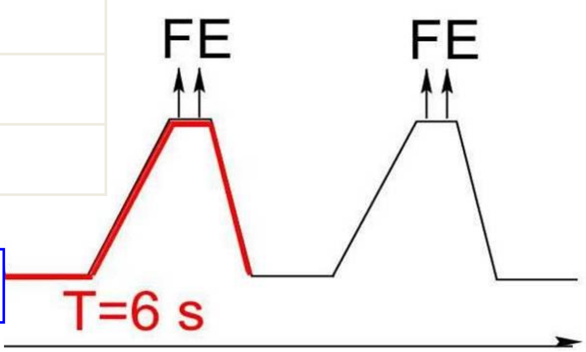

CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN
Excavated
Concreted
Decay tube (2nd contract)
55m
TJ8
Access shaft PGCN
SPS/ECA4
SPS tunnel
protons
TT41
Access galleries
target
TCV4 sump 30 m^3
LHC/TI8 tunnel
magnetic horns
Target chamber
Service gallery
LEP/LHC tunnel
TSG4 sump 30 m^3
140m
pions kaons
Decay tunnel
decay tunnel
TNM41 sump 8 m^3
hadron absorber
Hadron stop and first muon detector
muon detector 1
TZ sump 8 m^3
Connection gallery to TI8/LHC
muons neutrinos
muon detector 2
Second muon detector
TNM42 sump 8 m^3
neutrinos to Gran Sasso
06 / 2003
CERN-AC-DI-MM

CNGS Proton Beam Parameters

Beam parameters	Nominal CNGS beam
Nominal energy [GeV]	400
Normalized emittance [μm]	H=12 V=7
Emittance [μm]	H=0.028 V= 0.016
Momentum spread Δp/p	0.07 % +/- 20%
# extractions per cycle	2 separated by 50 ms
Batch length [μs]	10.5
# of bunches per pulse	2100
Intensity per extraction [10^{13} p]	2.4
Bunch length [ns] (4σ)	2
Bunch spacing [ns]	5
Beta at focus [m]	hor.: 10 ; vert.: 20
Beam sizes at 400 GeV [mm]	0.5 mm
Beam divergence [mrad]	hor.: 0.05; vert.: 0.03

500kW beam power

Expected beam performance: 4.5 x 10^{19} protons/year on target



Primary Beam Line

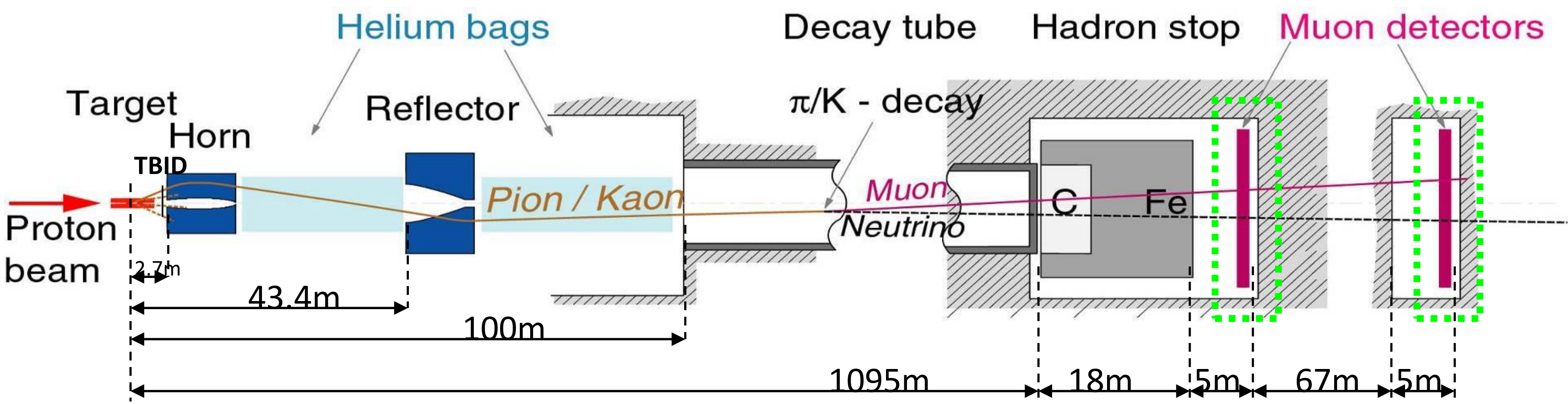
100m extraction together with LHC, 620m long arc to bend towards Gran Sasso, 120m long focusing section

Magnet System:

- 73 MBG Dipoles
  - 1.7 T nominal field at 400 GeV/c
- 20 Quadrupole Magnets
  - Nominal gradient 40 T/m
- 12 Corrector Magnets

CNGS Neutrino Production

$$p + C \rightarrow \text{(interactions)} \rightarrow \pi^+,\ K^+ \rightarrow \text{(decay in flight)} \rightarrow \mu^+ + \nu_\mu$$



Air cooled graphite target

- Target table movable horizontally/vertically for alignment
- Target TBID, ionization chambers

- 2 horns (horn and reflector)
  - Water cooled, pulsed with 10ms half-sine wave pulse of up to 150/180kA
- Decay pipe:
  - 1000m, diameter 2.45m, 1mbar vacuum,
- Hadron absorber:
  - Absorbs 100kW of protons and other hadrons
- 2 muon monitor stations: muon fluxes and profiles

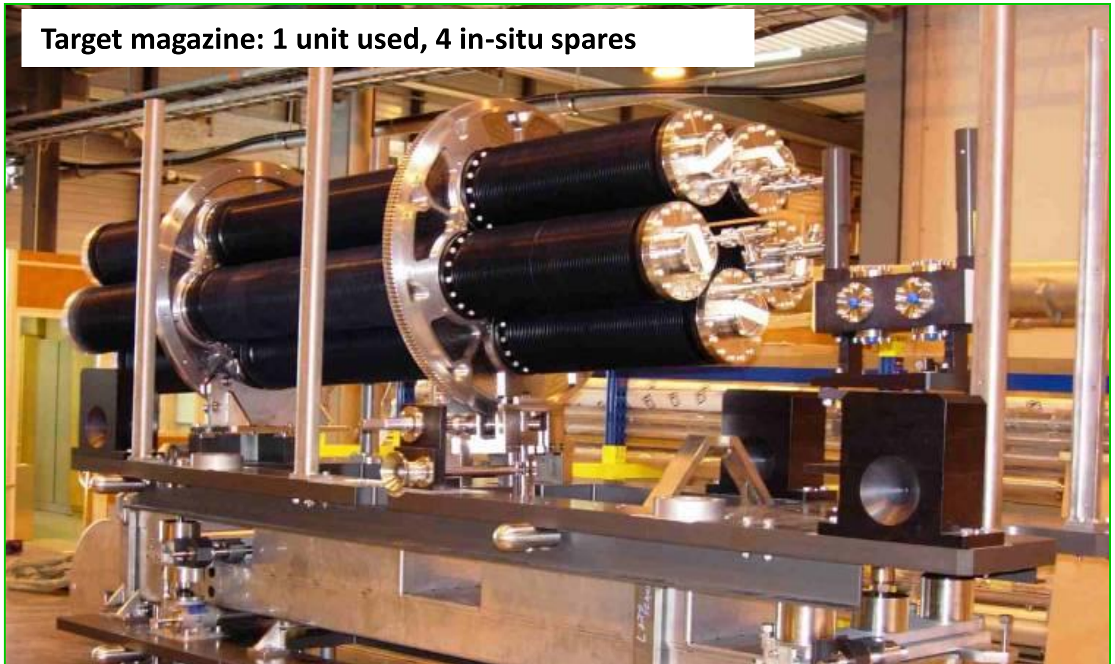
CNGS Target

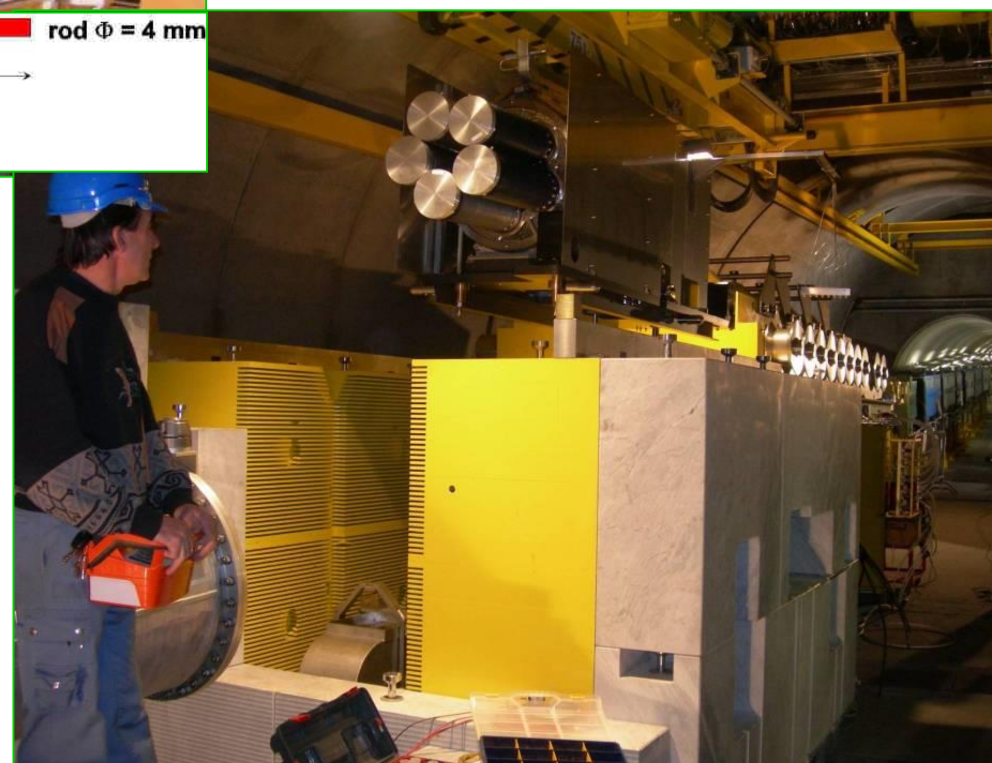
13 graphite rods, each 10cm long,

Ø = 5mm and/or 4mm

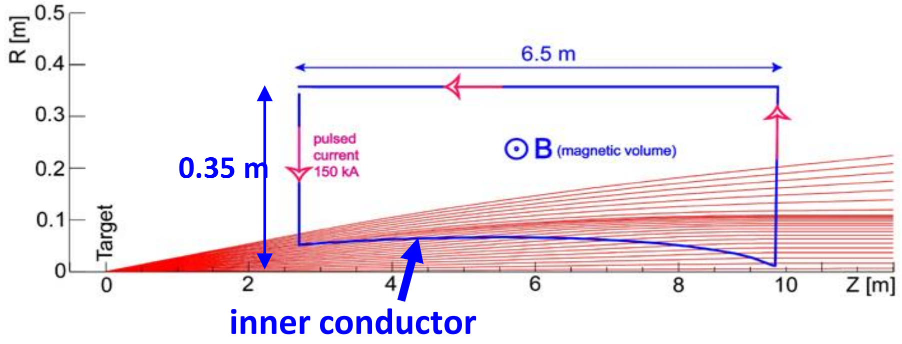
2.7mm interaction length

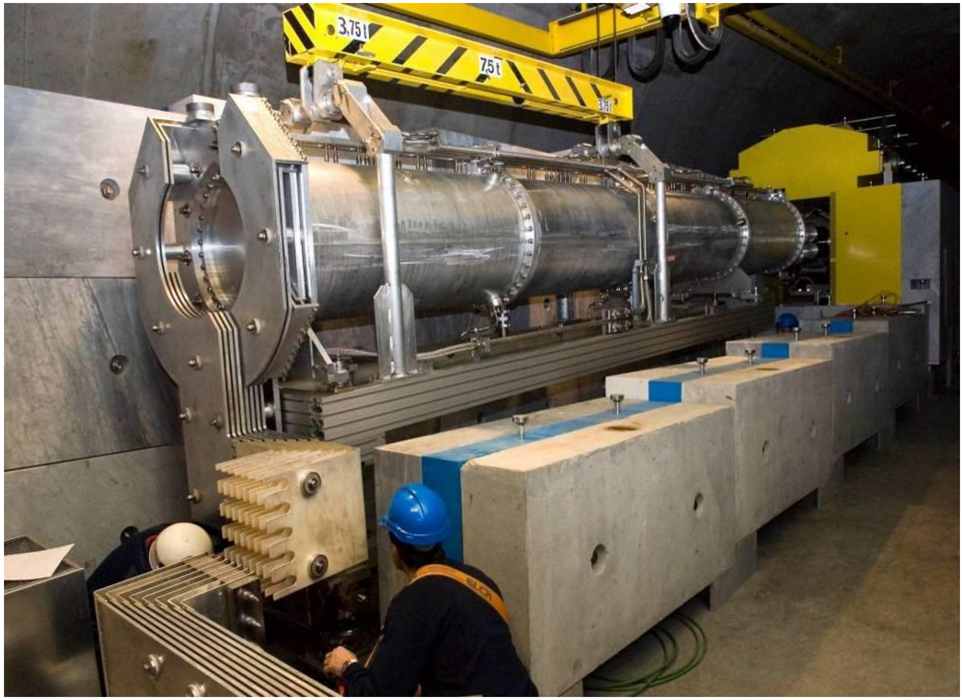
Ten targets (+1 prototype) have been built. → Assembled in two magazines.

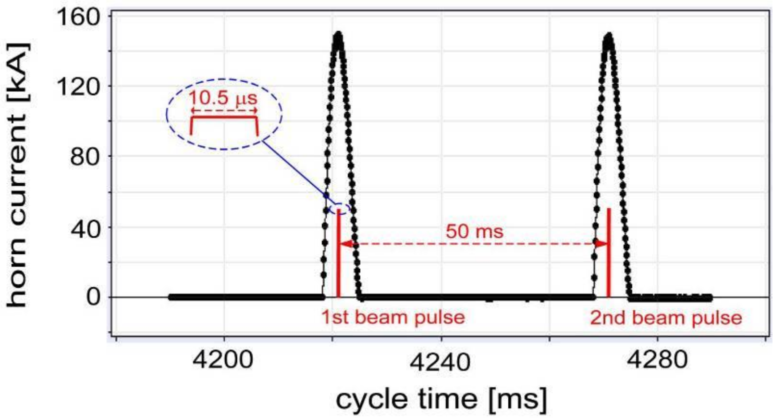




CNGS Horn and Reflector







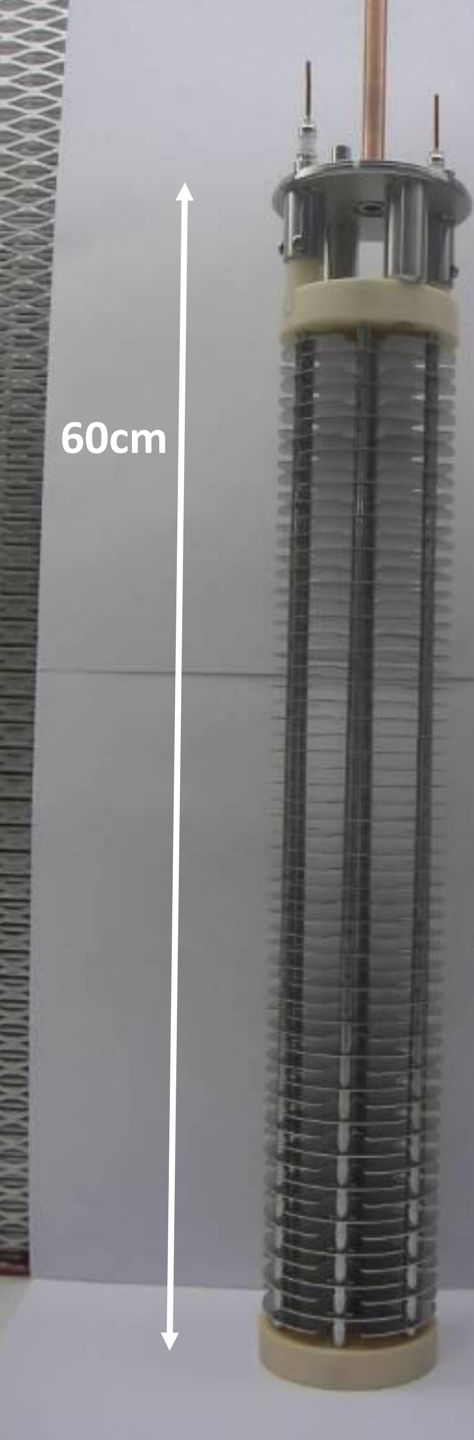
- 150kA/180kA, pulsed
- 7m long, inner conductor 1.8mm thick
- Designed for $2 \cdot 10^7$ pulses
- Water cooling to evacuate 26kW
- 1 spare horn (no reflector yet)

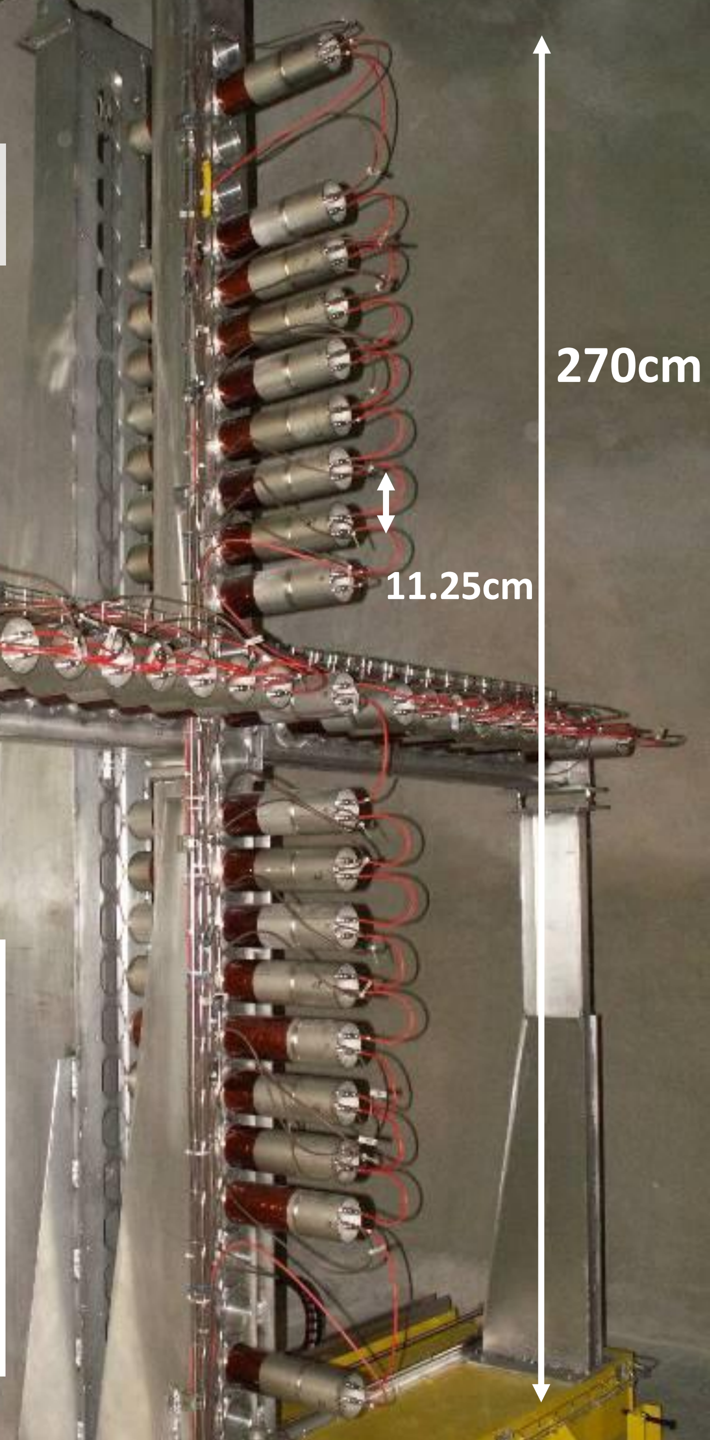
Decay Tube

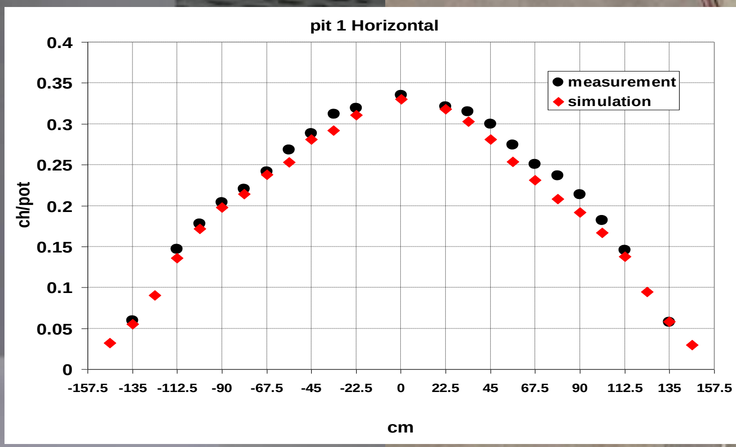
- steel pipe
- 1mbar
- 994m long
- 2.45m diameter, t=18mm, surrounded by 50cm concrete
- entrance window: 3mm Ti
- exit window: 50mm carbon steel, water cooled

Muon Monitors

- 2 x 41 fixed monitors (Ionization Chambers)
- 2 x 1 movable monitor

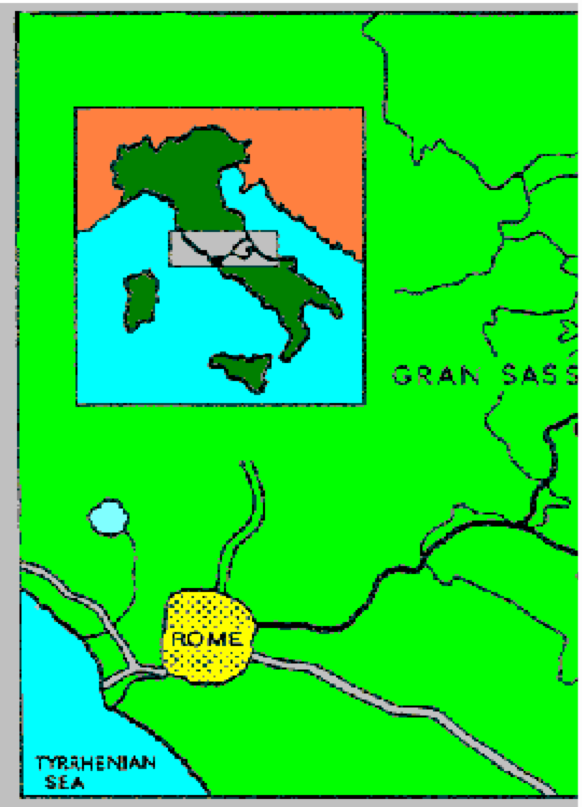


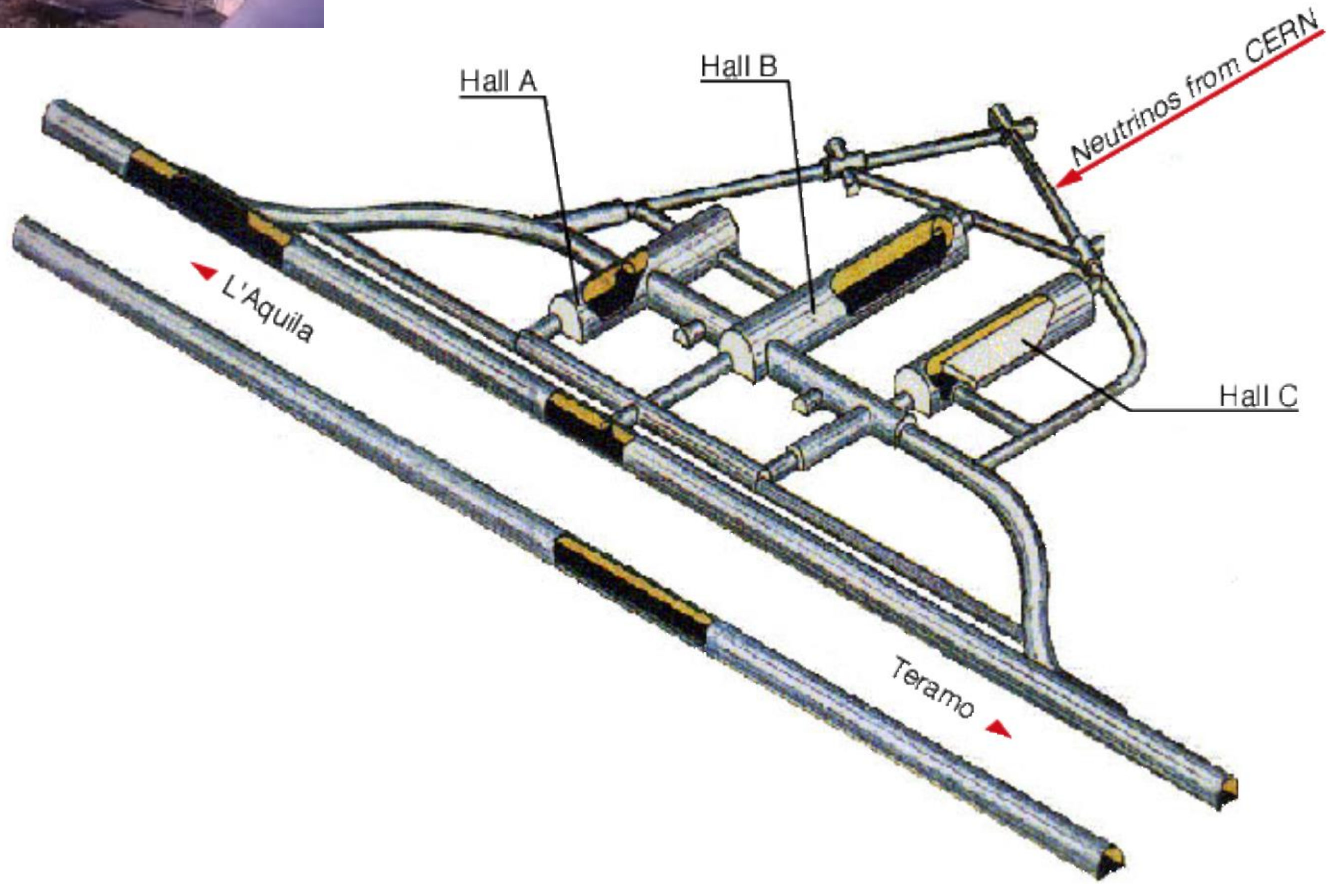




The Gran Sasso Laboratory (LNGS)

Existing laboratory with its infrastructure (since 1987)
Large halls directed to CERN
Caverns in the GS mountains: 1500 m of rock shielding
Tradition in very successful neutrino physics experiments (solar neutrinos)



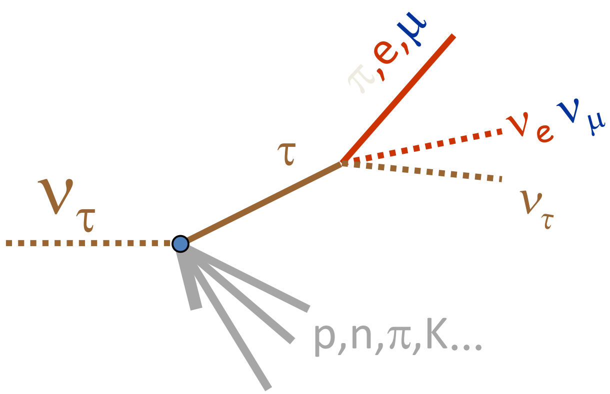


Detecting ν_τ at Gran Sasso

Look for the τ lepton :

➔ extremely difficult:

τ travels only less than **1 mm** before decaying



5 years CNGS operation, 1800 tons target:

- 30000 neutrino interactions
- ~150 ν_τ interactions
- ~15 ν_τ identified
- < 1 event of background

Approach:

➔ very good position resolution (see the decay 'kink'): OPERA

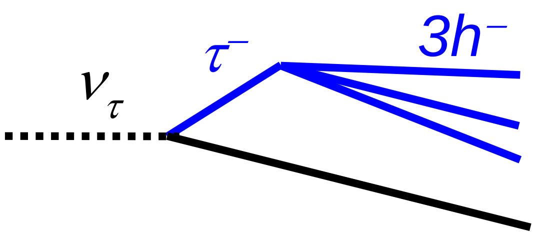
OPERA

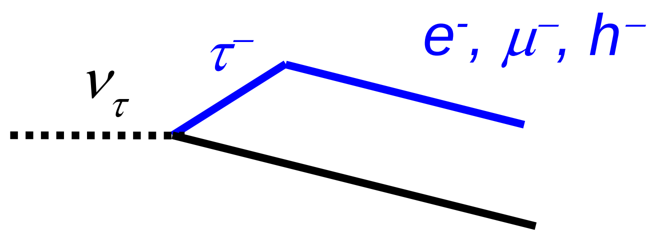
How to Detect a Tau Neutrino?

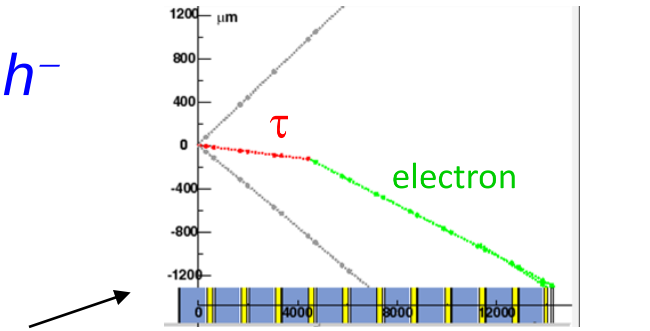
→ ν_τ interaction in the target produces a τ lepton.
→ τ lepton: very short lifetime

Tau lifetime: $2.9 \cdot 10^{-13}$s
→c*lifetime: 87 μm

→ Identification of tau by the characteristic ‘**kink**’ on the decay point.







CNGS:
tau: lorenzboost of ~10:
→Tau tracklength: ~1mm

First direct measurement of ν_τ only in 2000 by DONUT (Detector for Observation of Tau Neutrino) at Fermilab → Emulsion target

- Need high resolution detector to observe the kink
- Large mass due to small interaction probability

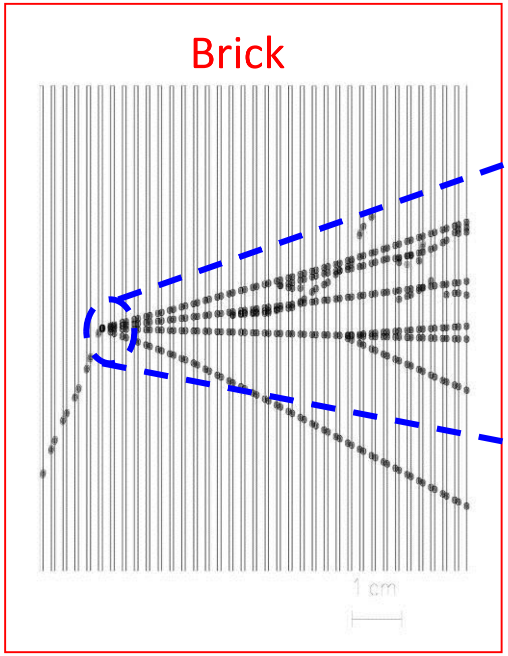
Gran Sasso:
→OPERA (1.2kton) emulsion target detector: ~146000 lead-emulsion bricks
→ICARUS (600ton) liquid argon TPC

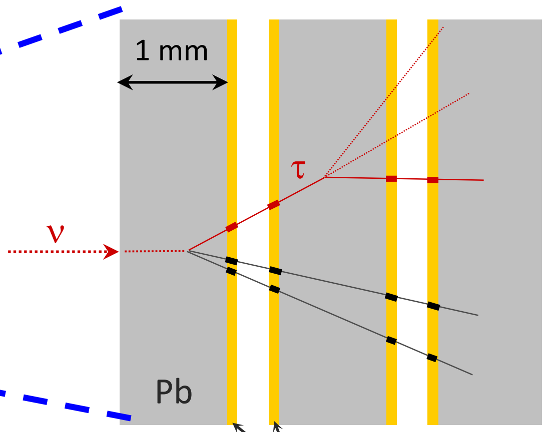
OPERA Experiment

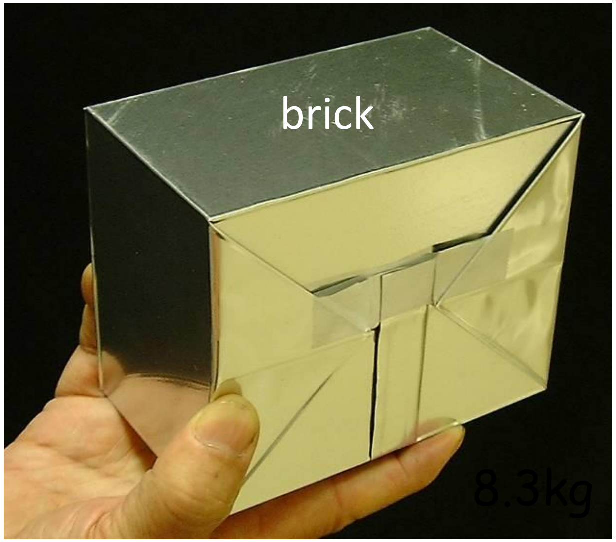
Basic unit: brick:

56 Pb sheets + 56 photographic films (emulsion sheets)

lead plates: massive target
emulsions: micrometric precision



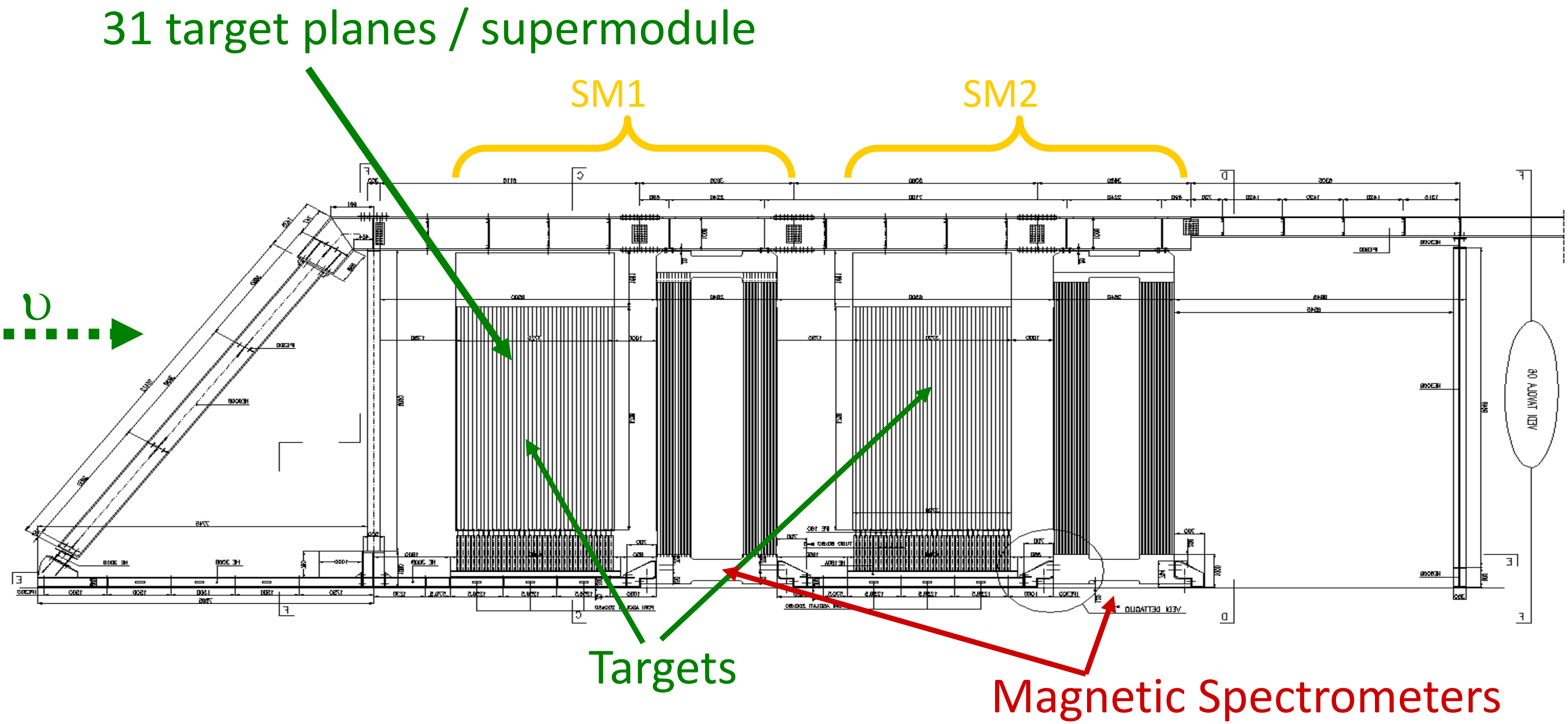




10.2 x 12.7 x 7.5 cm^3

Structure of the OPERA Experiment

In total: ~146621 bricks, 1200 tons

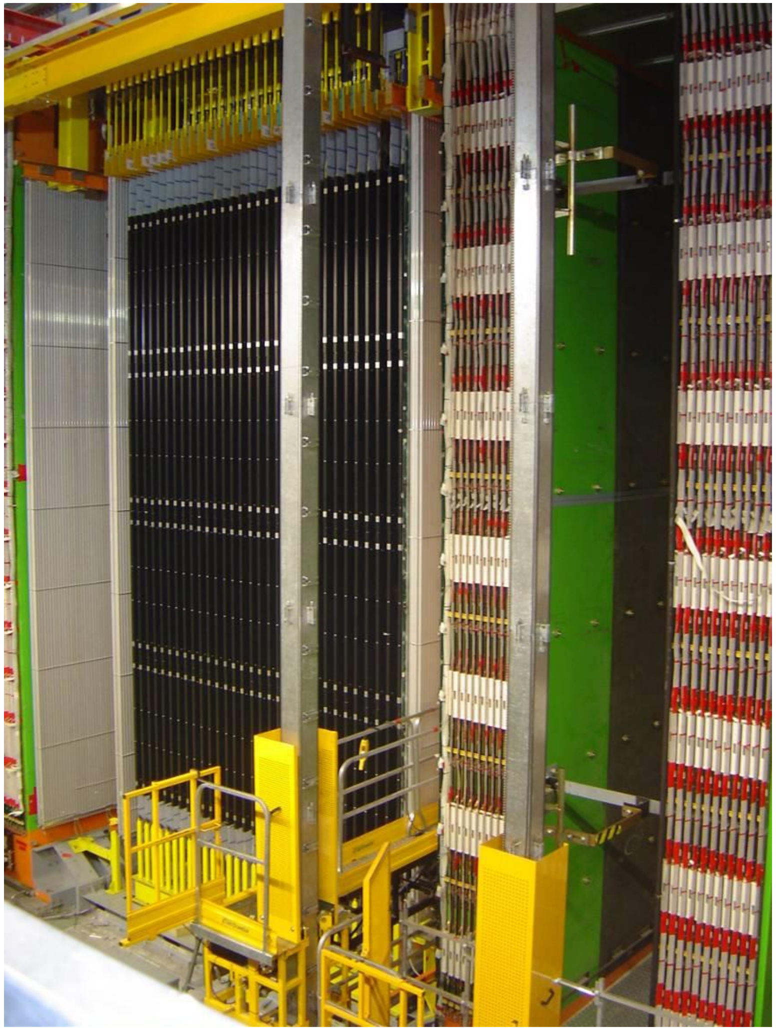


5 years CNGS operation, 1200 tons target:

- 20000 neutrino interactions
- ~100 ν_τ interactions
- ~10 ν_τ identified
- < 1 event of background

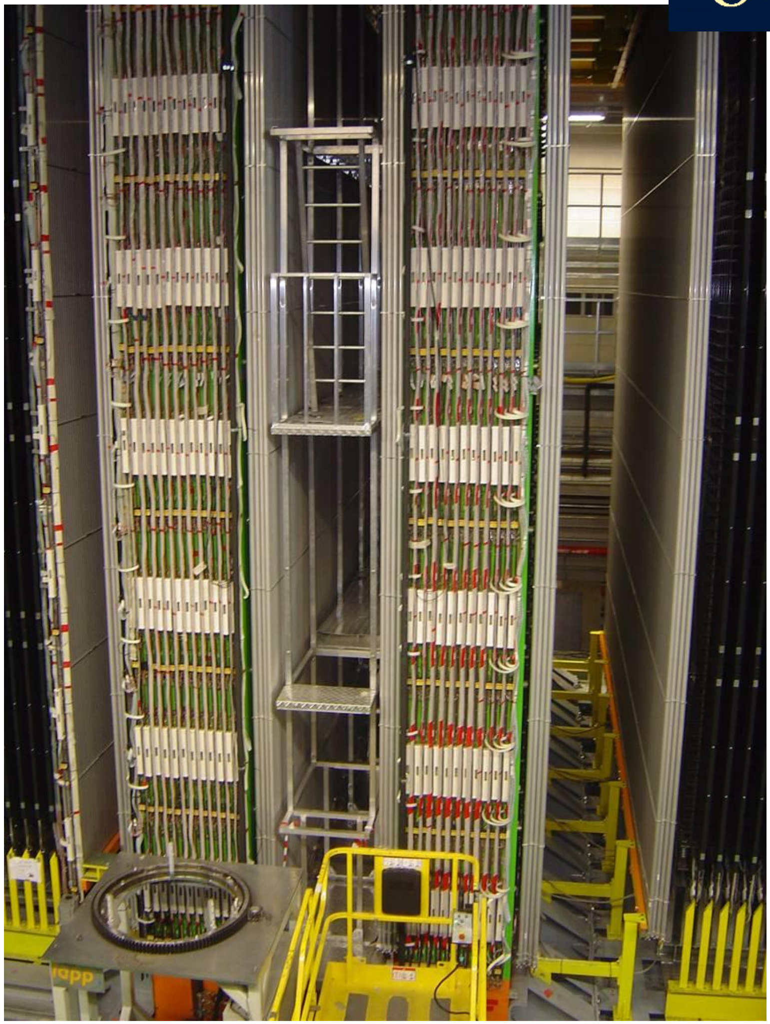
OPERA in Pictures

Second Super-module



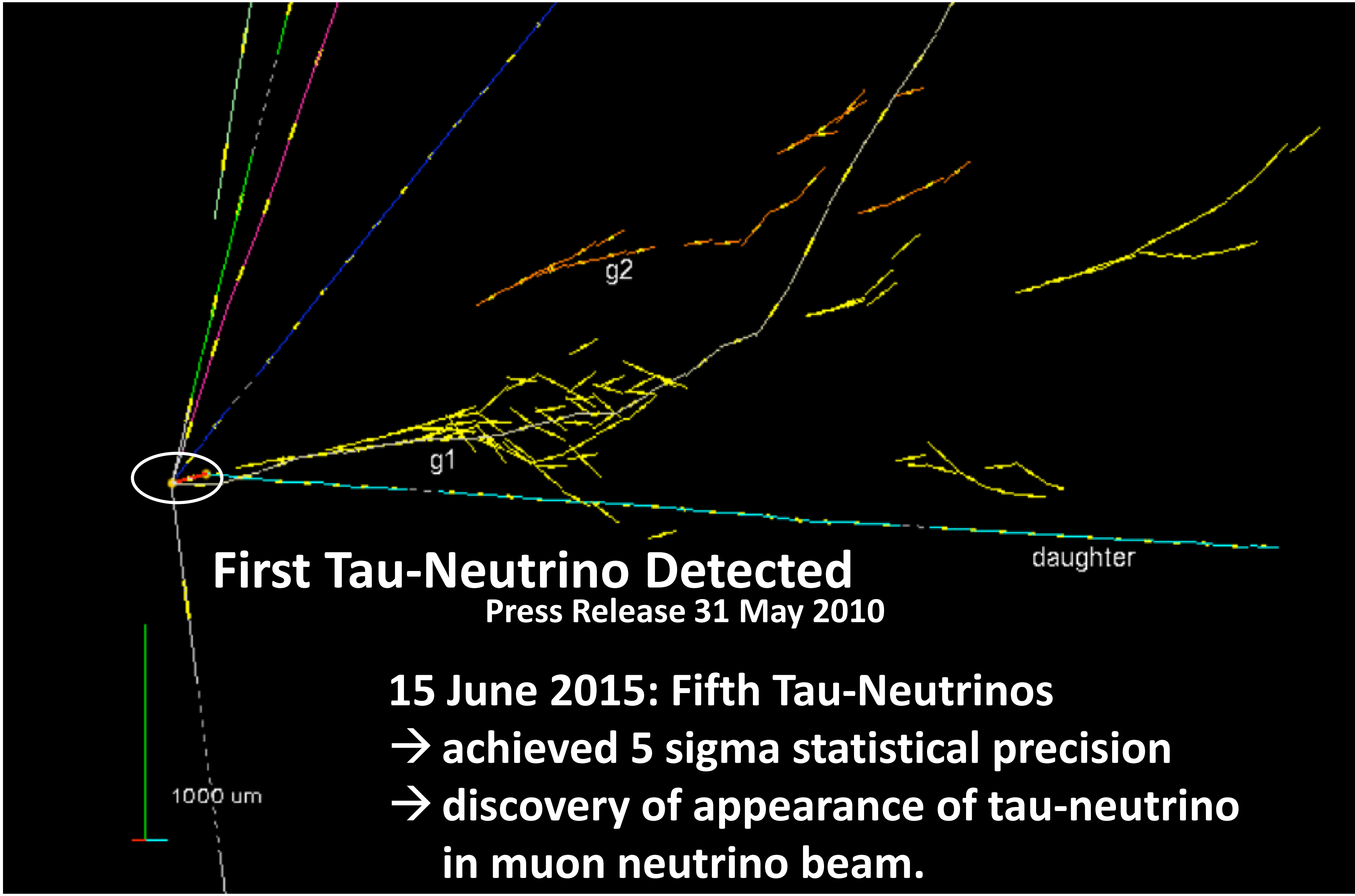
Scintillator planes 5900 m^2
8064 7m long drift tubes

Details of the first spectrometer



3050 m^2 Resistive Plate Counters
2000 tons of iron for the two magnets

CNGS



First Tau-Neutrino Detected

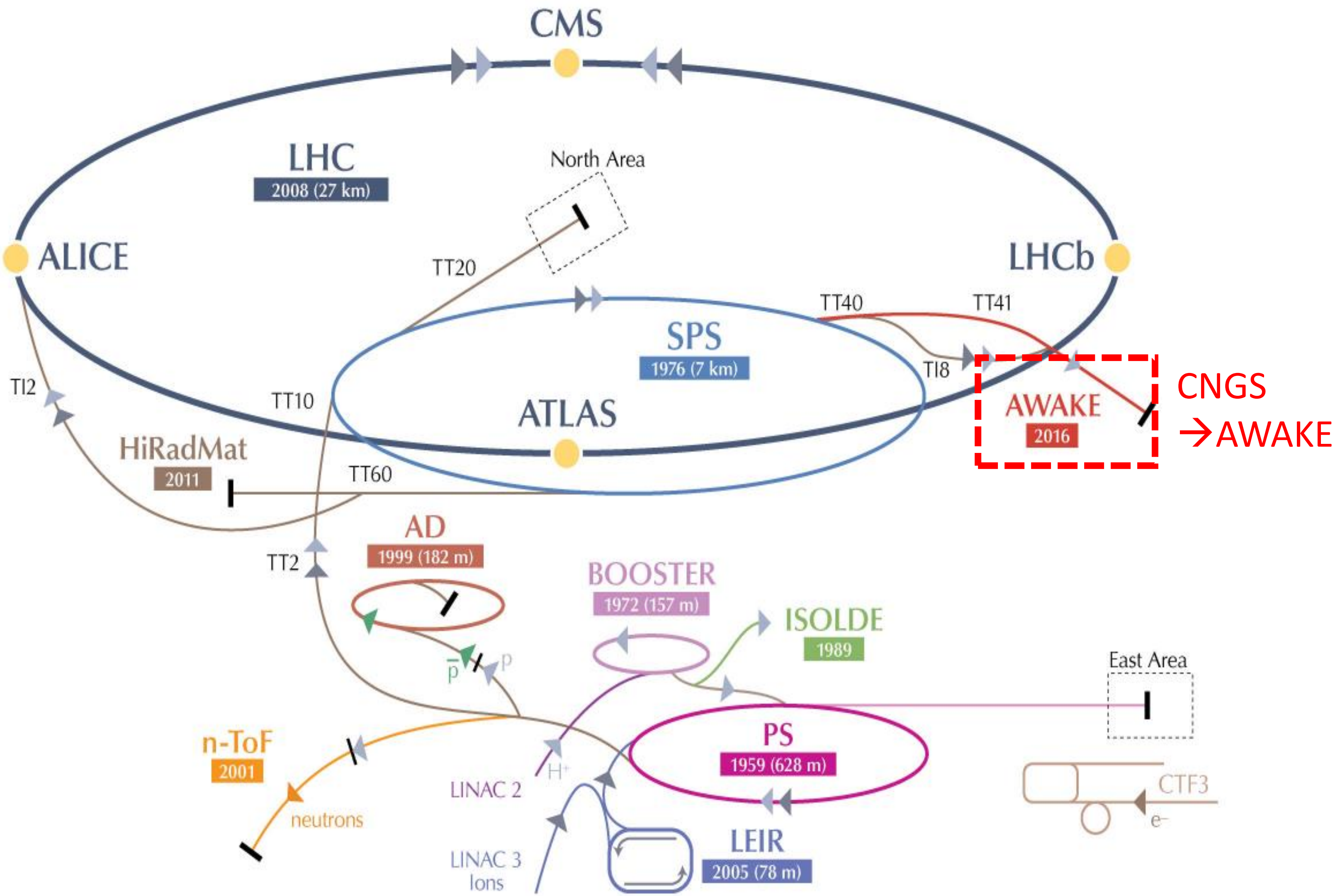
Press Release 31 May 2010

15 June 2015: Fifth Tau-Neutrinos

→ achieved 5 sigma statistical precision

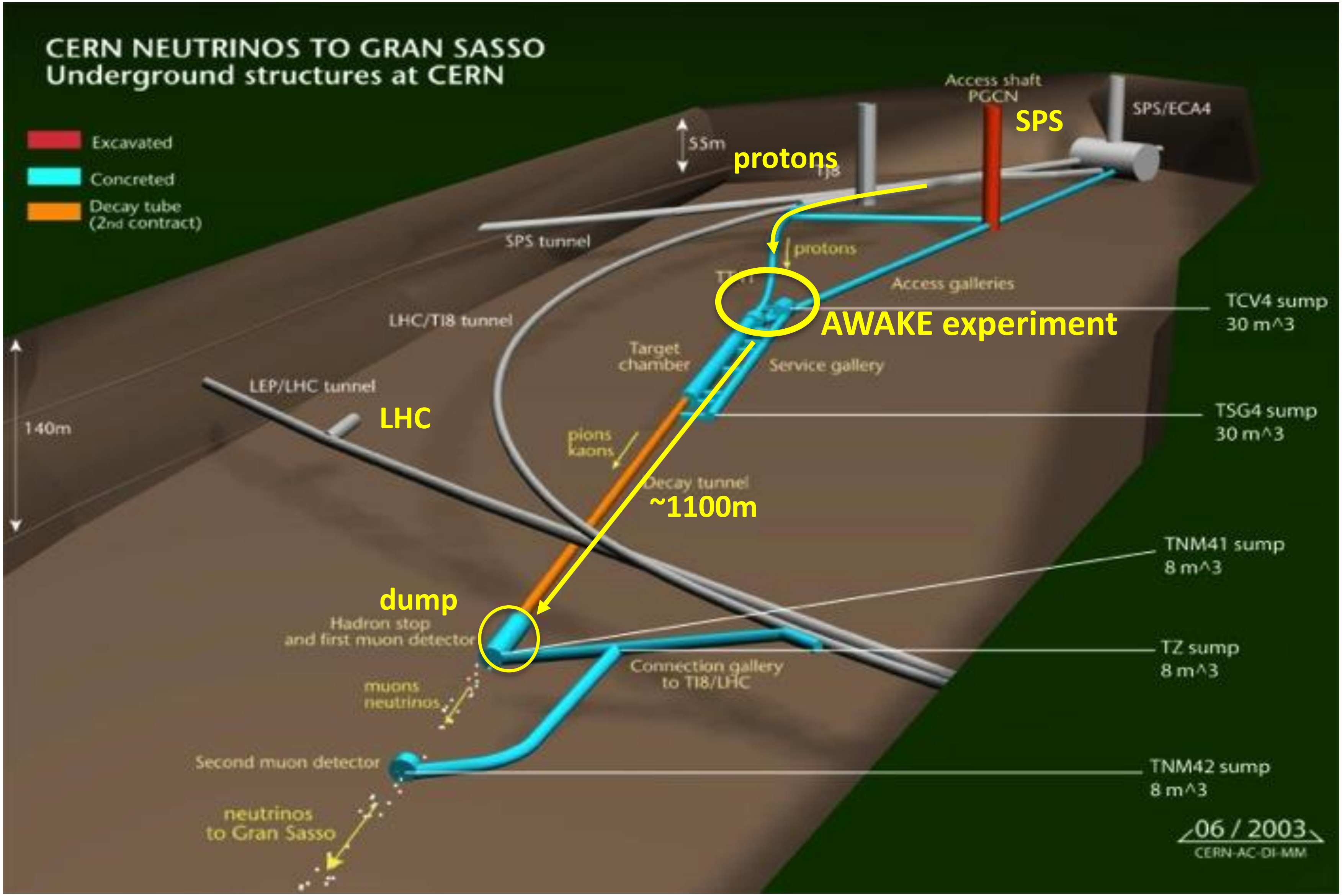
→ discovery of appearance of tau-neutrino in muon neutrino beam.

CERN Accelerator Complex



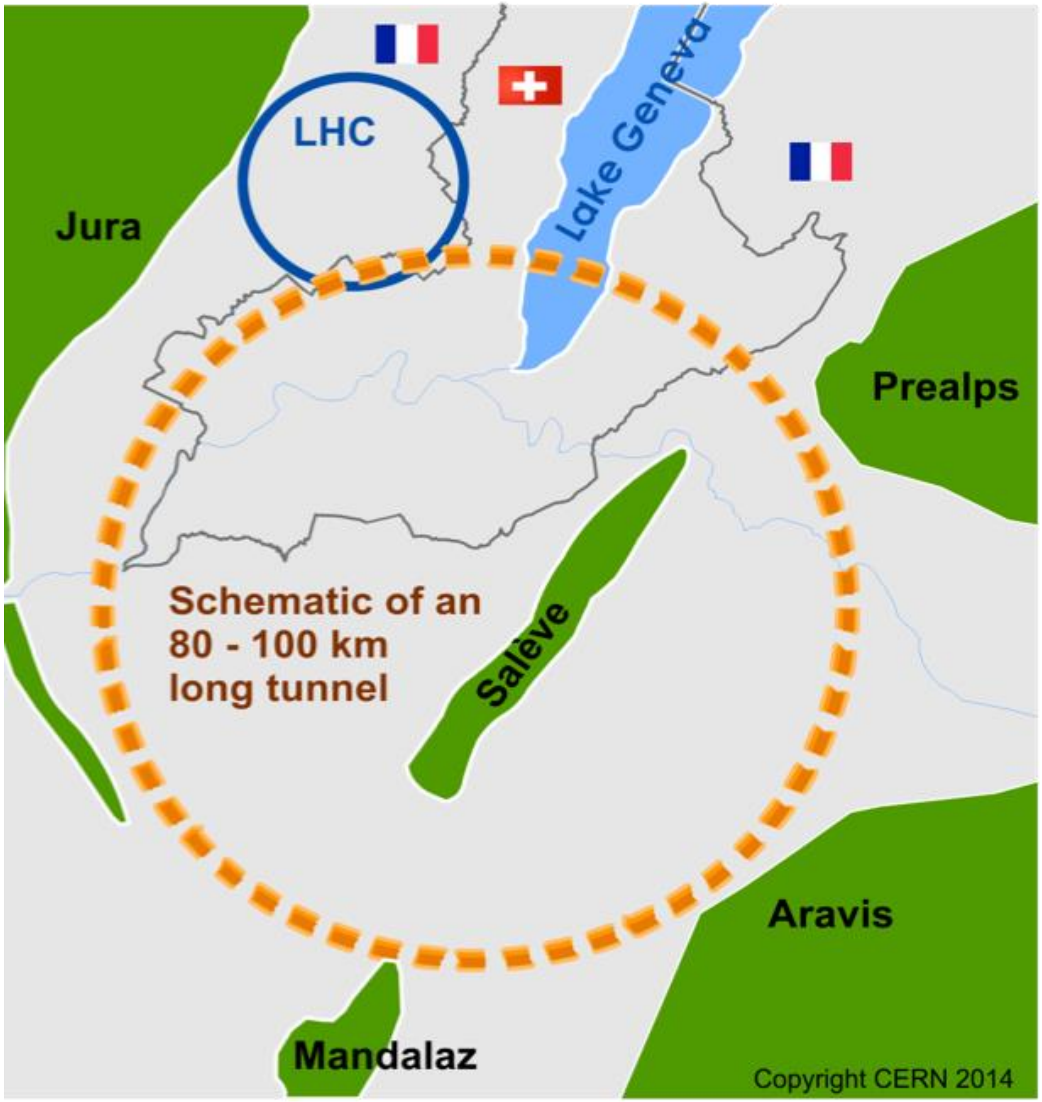
AWAKE: Advanced Proton Driven Plasma Wakefield Acceleration Experiment at CERN

AWAKE at CERN



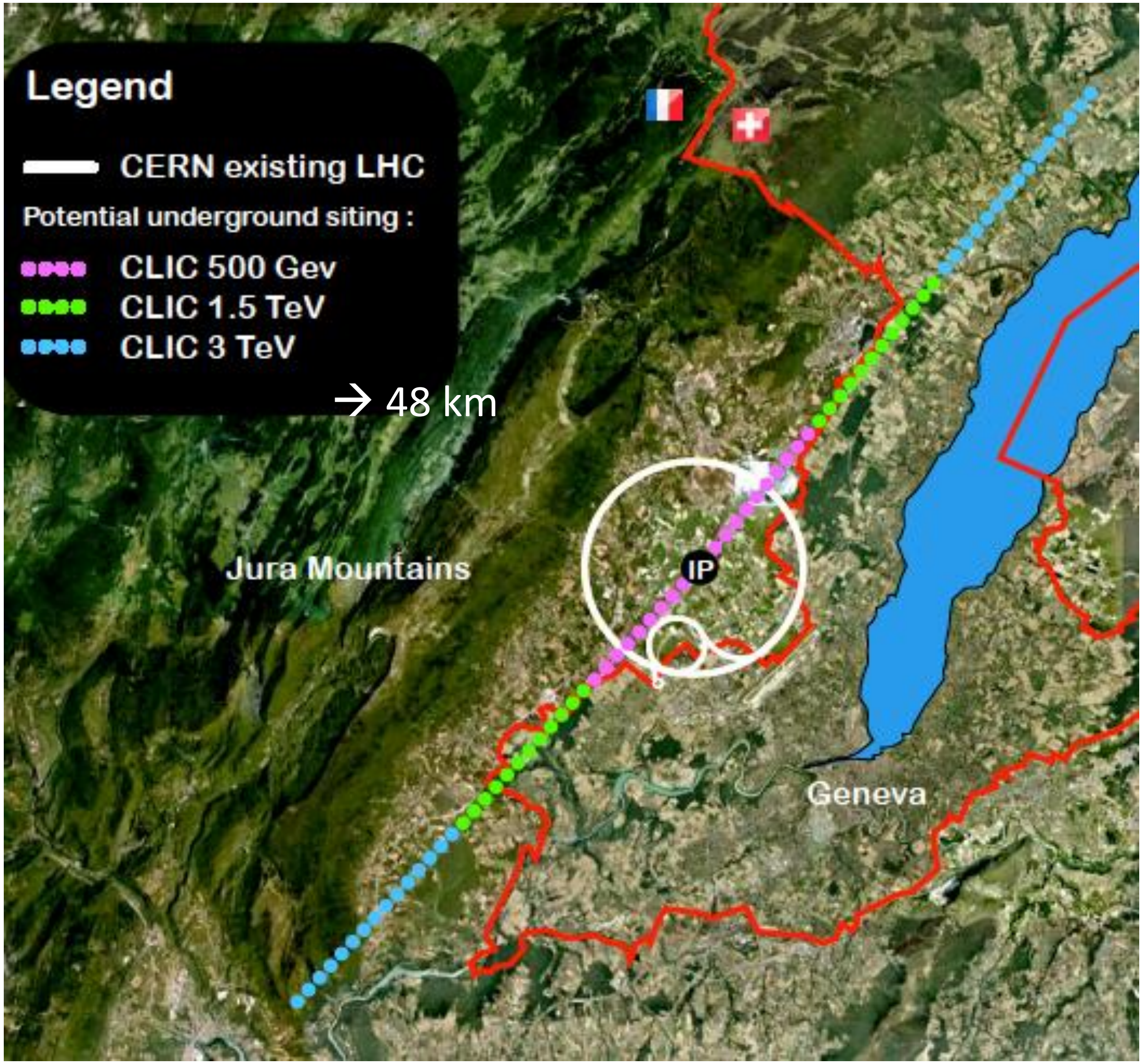
Why?

Future lies in high energy accelerators at the TeV range!



Why?

Linear Colliders: CLIC, ILC



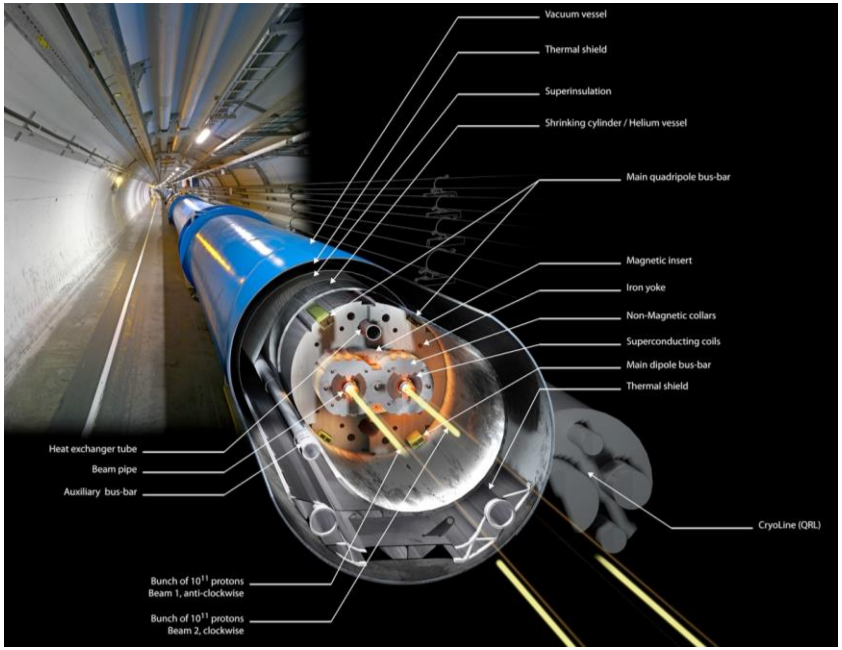
→ Bigger colliders: more expensive!

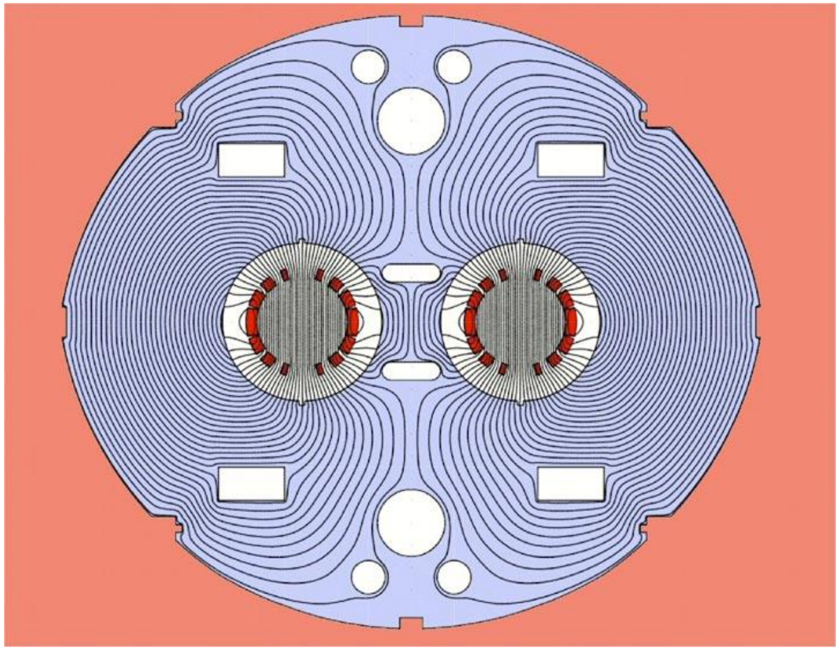
Why?

Key elements for accelerators:

- Magnets (Dipoles)
  1. LHC: 8.3 Tesla
  2. FCC: 20 Tesla

  ➔ Use superconducting magnets to reach these fields!!



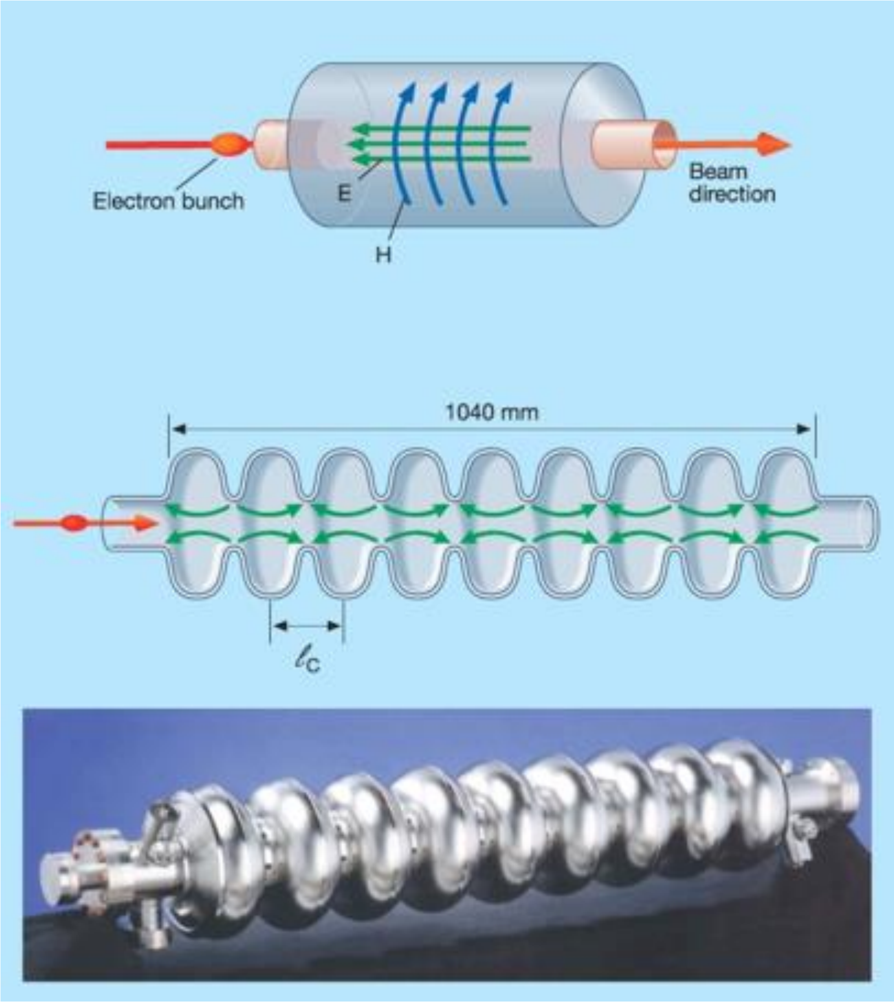


Why?

Key elements for accelerators:

- Accelerating elements (cavities)
  1. LHC: 5 MV/m
  2. CLIC: 100MV/m

  → Use superconducting technology to reach a strong gradient!



Motivation – Cavities vs Plasma

Today's RF cavities or microwave technology: accelerating fields is limited to <100 MV/m

→ several **tens of kilometers for future linear colliders**

- Typical gradients:
  - LHC: 5 MV/m
  - ILC: 35 MV/m
  - CLIC: 100 MV/m

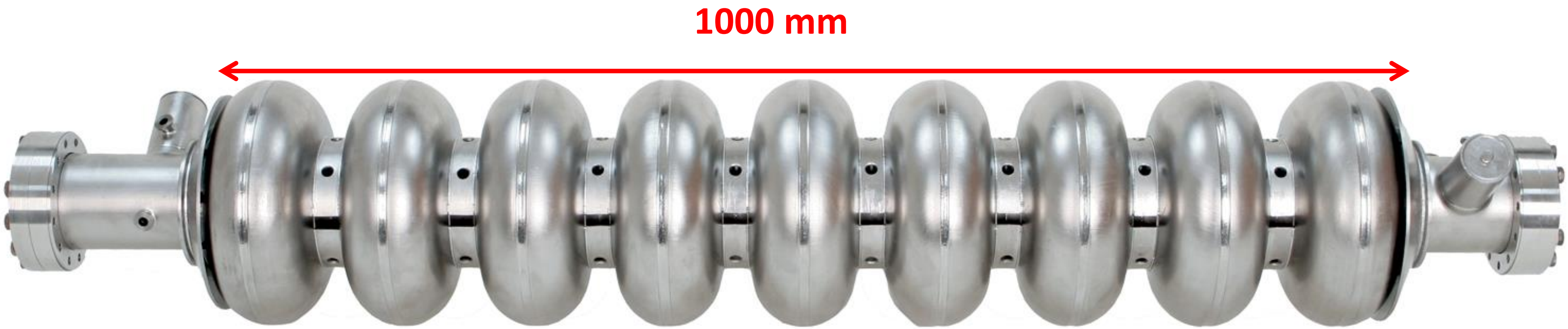
Use plasma as 'cavity'!

- Plasma can sustain up to **three orders of magnitude higher gradients**
  - SLAC experiment: **50 GV/m**

→ **much shorter linear colliders!**

Motivation – Cavities vs. Plasma

- ILC Cavity: 35 MV/m

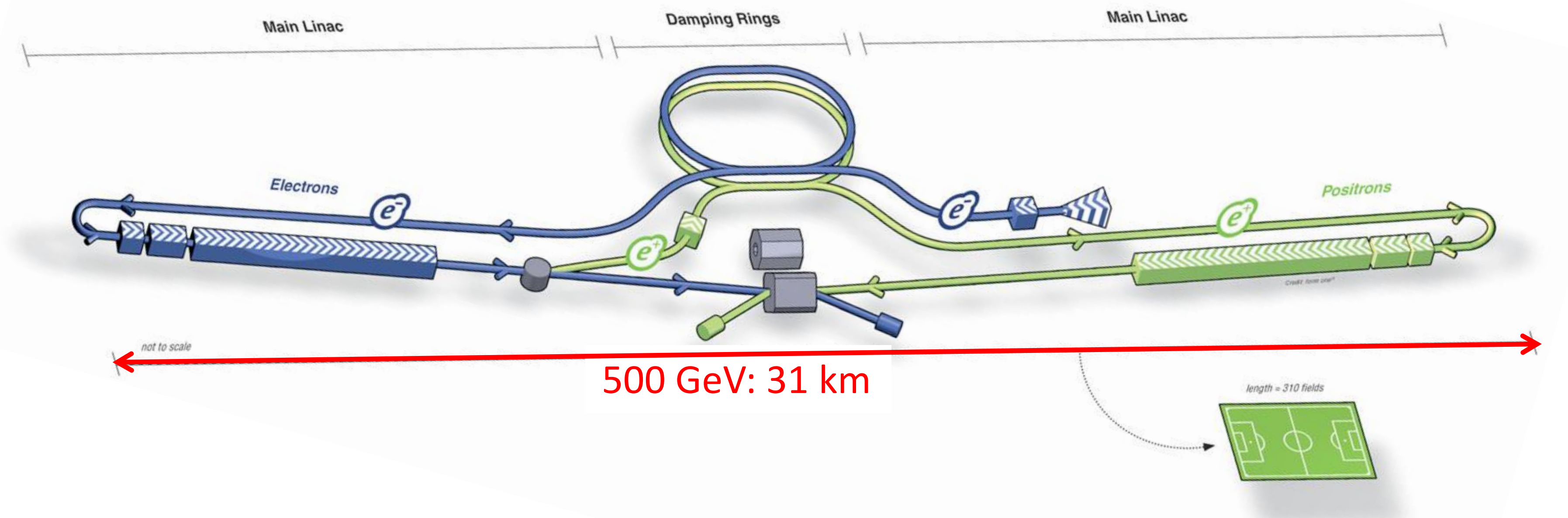


- Plasma cell: 35 GV/m → **35 MV/mm!!**

(Not to scale!)

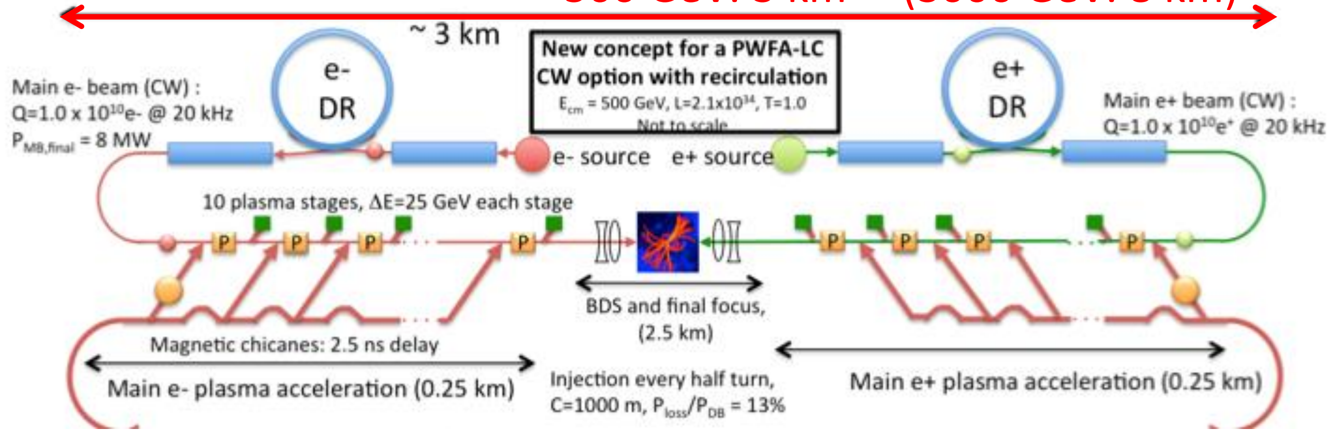
Motivation – Linear Colliders

ILC



Plasma based Linear Collider

500 GeV: 3 km (3000 GeV: 8 km)



Principle of Plasma Wakefield Acceleration

TEDxCERN

x = independently organized TED event

Videos | Speakers | Interactive story | Participate | Partners | About

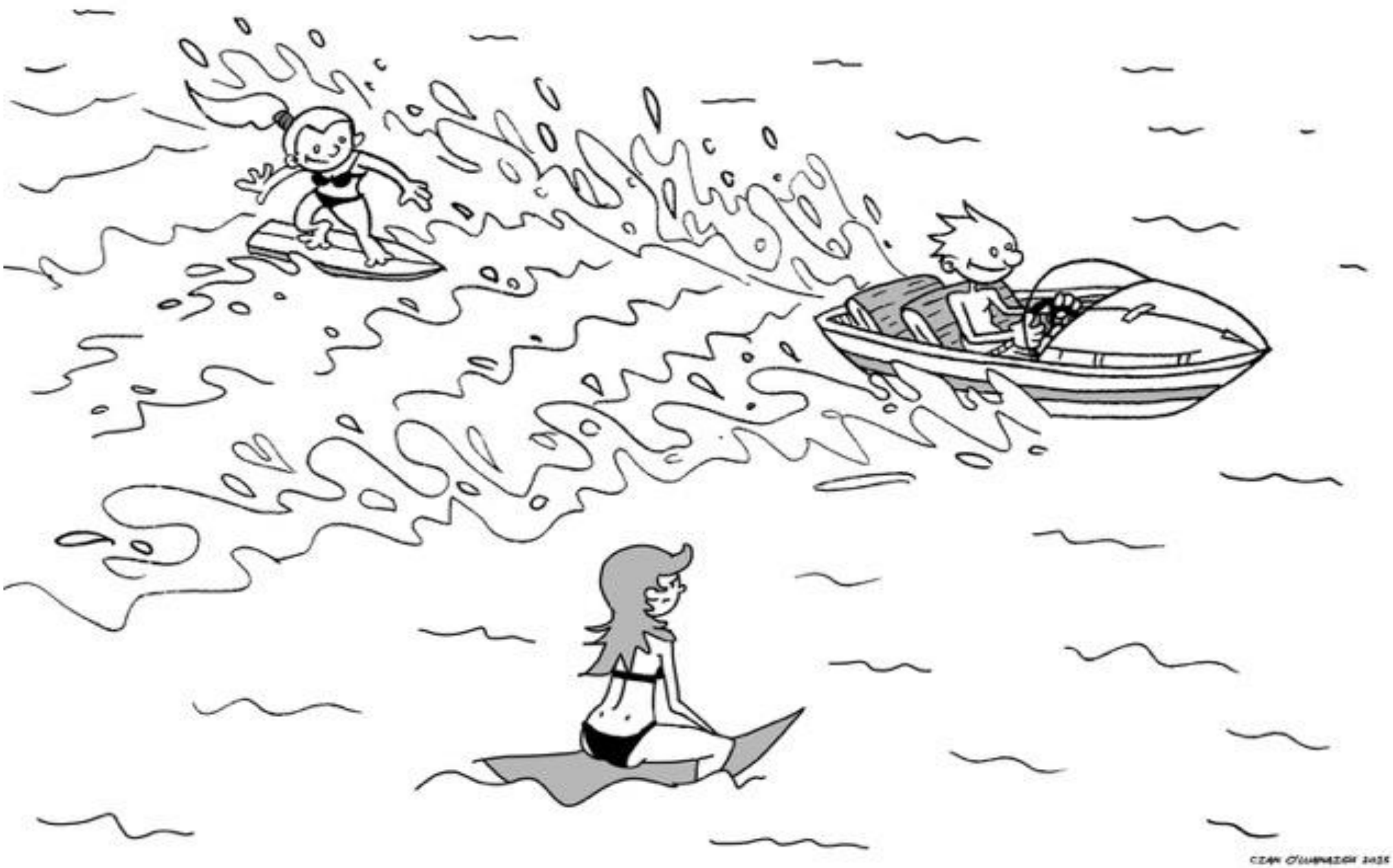
Surfing wakefields to create smaller accelerators

CERN is famous for its big machines, for studying the tiniest constituents of matter to answer the biggest questions about the universe. Edda Gschwendtner is looking at radical yet simple ways of making our enormous machines smaller and more affordable.

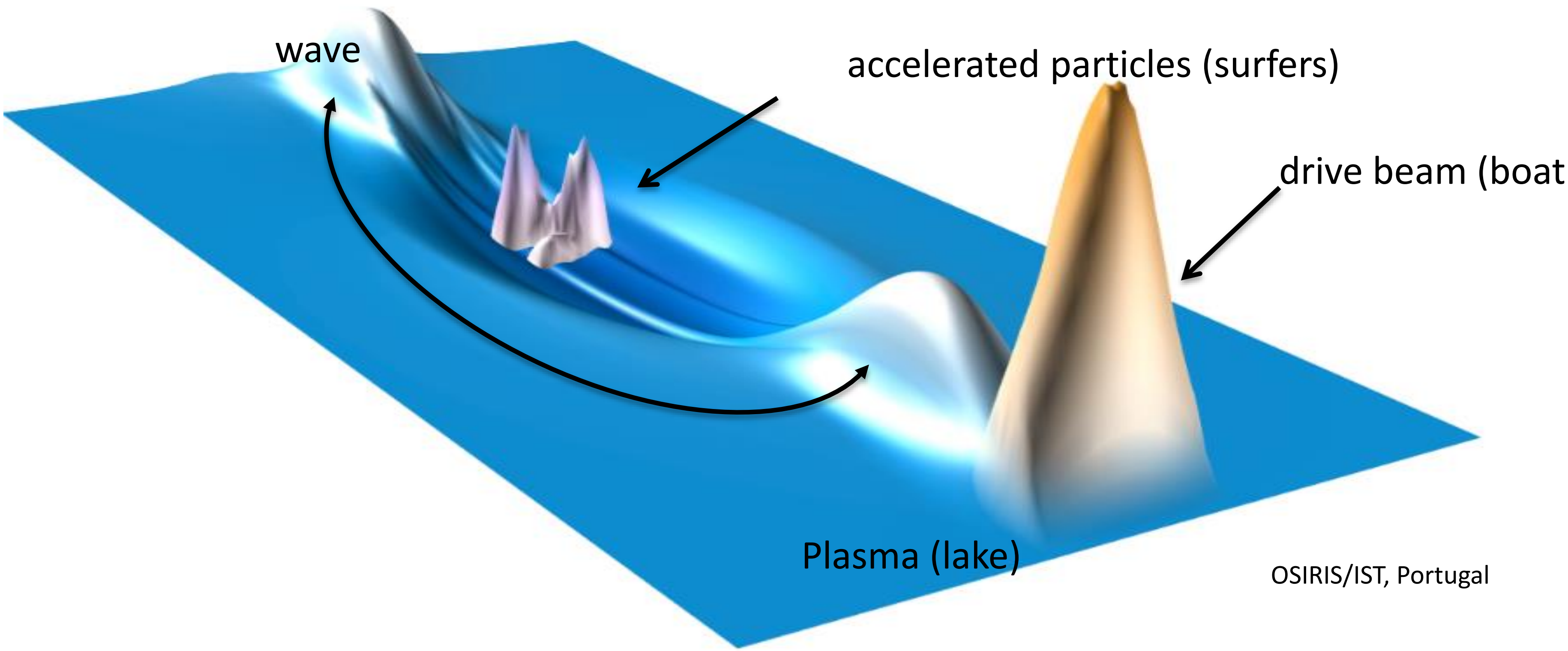
TEDxCERN 9 October 2015
http://tedxcern.web.cern.ch/

Video:
https://youtu.be/5Ryp6UTCeUo

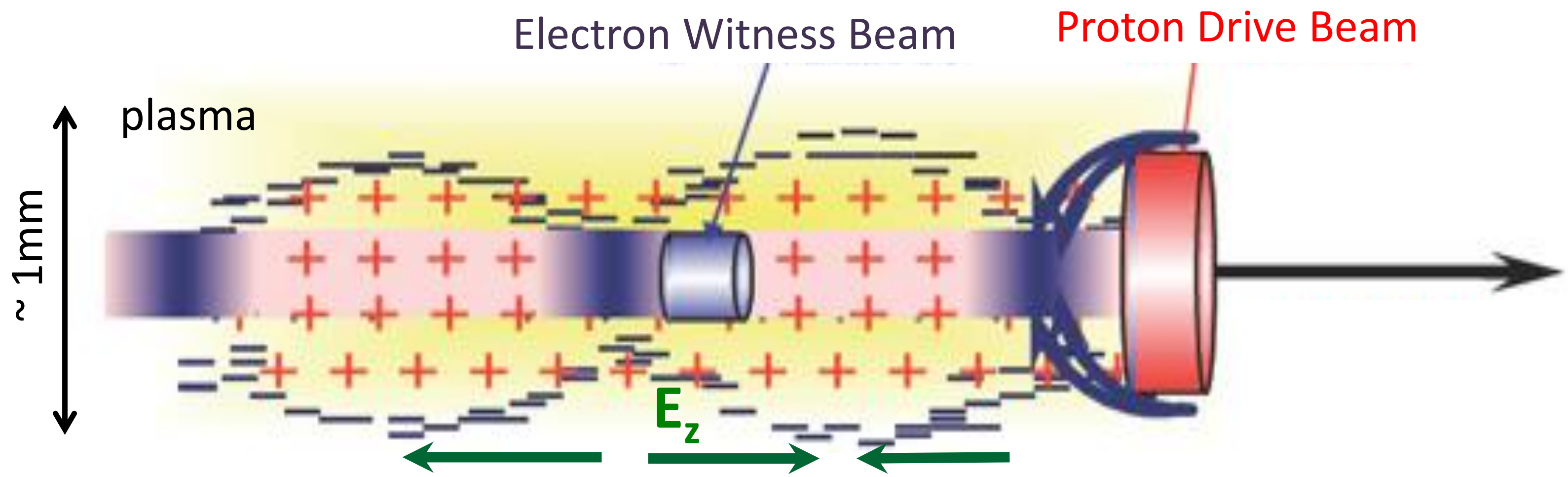
Principle of Plasma Wakefield Acceleration



Principle of Plasma Wakefield Acceleration



Principle of Plasma Wakefield Acceleration



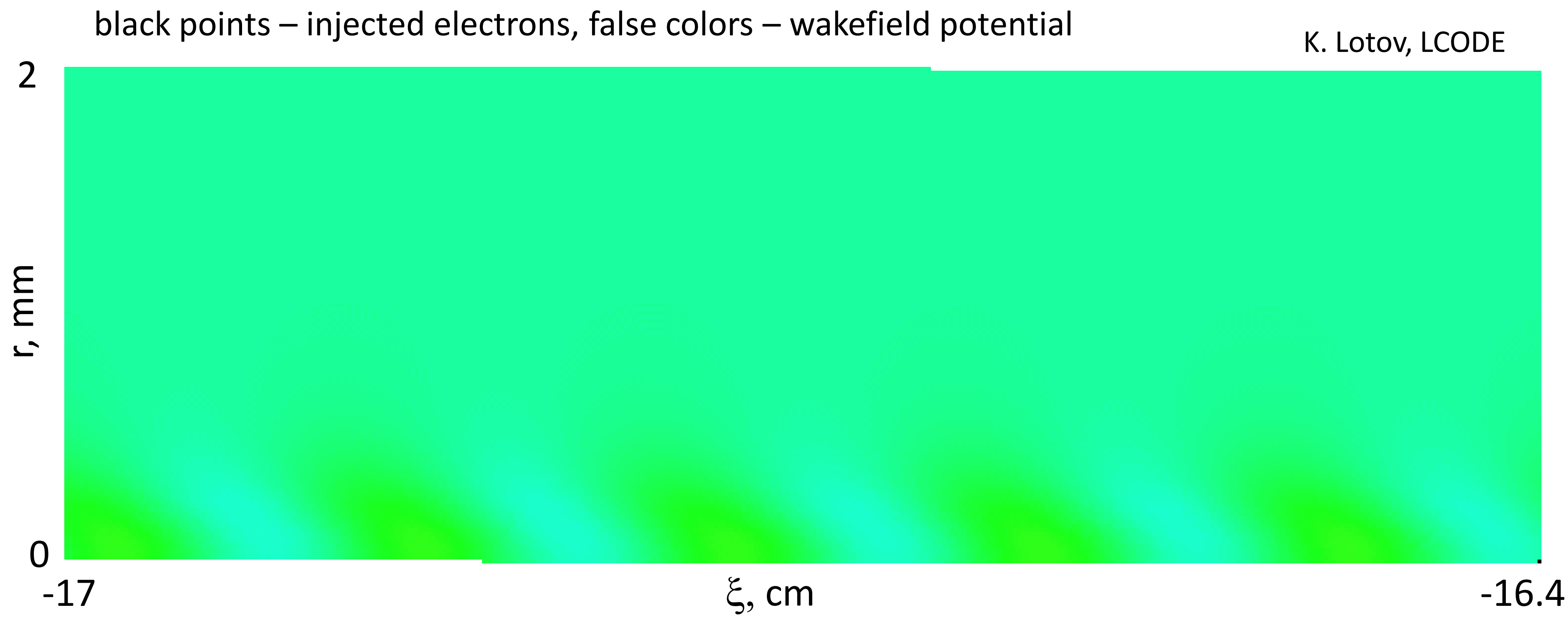
- Plasma wave is excited by a relativistic particle bunch.
- Space charge of drive beam displaces plasma electrons.
- Plasma electrons attracted by plasma ions, and rush back on-axis.

➔ Produce ‘mini cavities’ (~1mm) inside the plasma cell

→ Proton beam produces (*drives)* accelerating wakefield in the plasma

→ Injected electron beam surfs (*witnesses)* on that wakefield and gets accelerated.

Electron Beam Trapping and Acceleration in the Plasma Wakefield

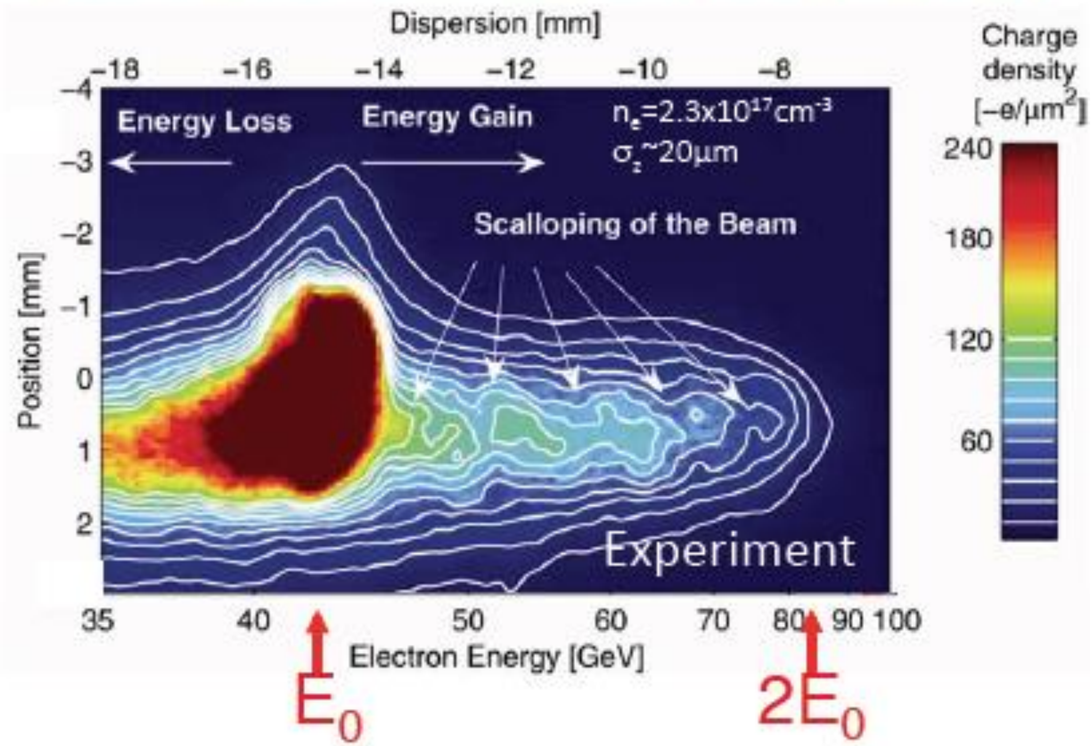


- Electrons are trapped from the very beginning by the wakefield
- Trapped electrons make several synchrotron oscillations in their potential wells
- After z=4 m the wakefield moves forward in the light velocity frame

First Results: Electron Beam Driven PWA

➔ Experimental results show success of PWFA and its research ➔ **SLAC beam:**

Blumenfeld, Nature 445, 741 (2007)



42 => 84GeV in 85cm! 50GeV/m

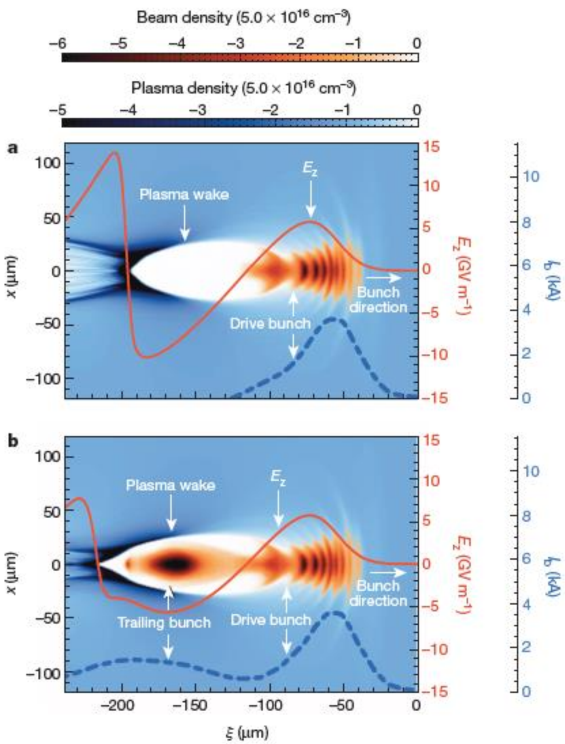
SLAC – FACET: Latest Results

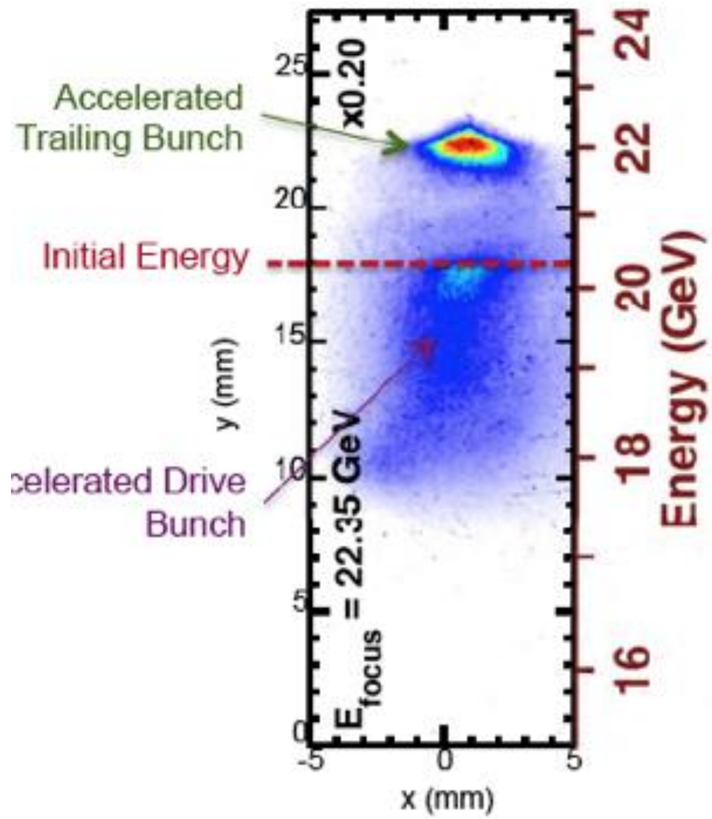
High-Efficiency acceleration of an electron beam in a plasmas wakefield accelerator

M. Litos et al., doi, Nature, 6 Nov 2014, 10.1038/nature 13992

Result

- **Total efficiency is <29.1%> with a maximum of 50%.**
- **Final energy spread of 0.7 % (2% average)**



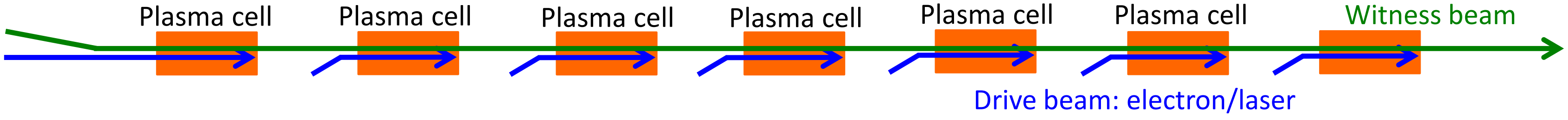


Laser or Electron Beam Driven PWA

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

  ➔ Today's electron beams usually < 100 J level.
  ➔ limitation of the energy carried by the drive beam (< 100J) and the propagation length of the driver in the plasma (<1m).

- To reach TeV scale with electron driven PWA: also need several stages, but need to have
  - relative timing in 10's of fs range
  - many stages
  - effective gradient reduced because of long sections between accelerating elements....



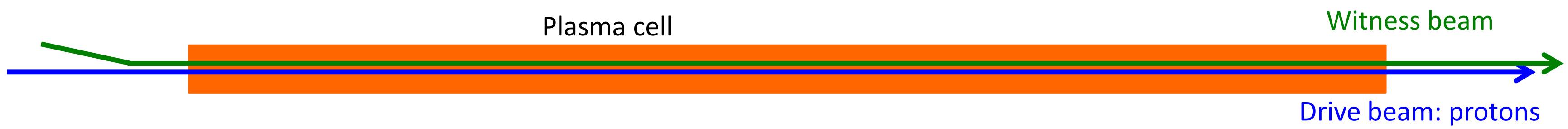
Proton Beam Driven PWA

Proton beams carry much higher energy:

- 19kJ for 3E11 protons at 400 GeV/c.
  - Drives wakefields over much longer plasma length, only 1 plasma stage needed.

Simulations show that it is possible to gain 600 GeV in a single passage through a 450 m long plasma using a **1 TeV p+** bunch driver of **10e11 protons** and an rms bunch length of **100 μm**.

A. Caldwell, K. Lotov, Physics of Plasma, 18,103101 (2011)



Protons are positively charged.

- They don't blow out the plasma electrons, they suck them in.
- The general acceleration mechanism is similar.

Beam-Driven Wakefield Acceleration: Landscape

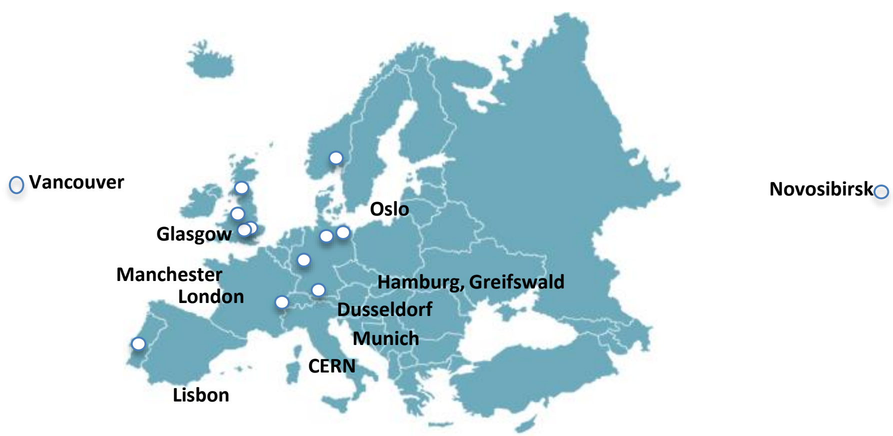
Facility	Where	Drive (D) beam	Witness (W) beam	Start	End	Goal
AWAKE	CERN, Geneva, Switzerland	400 GeV **protons**	Externally injected electron beam (PHIN 15 MeV)	2016	2020+	**Use for future high energy e-/e+ collider.** - Study Self-Modulation Instability (SMI). - Accelerate externally injected electrons. - Demonstrate scalability of acceleration scheme.
SLAC-FACET	SLAC, Stanford, USA	20 GeV **electrons** and **positrons**	Two-bunch formed with mask (e^-/e^+ and e^--e^+ bunches)	2012	Sept 2016	- Acceleration of witness bunch with high **quality and efficiency** - Acceleration of positrons - FACET II proposal for 2018 operation
DESY-Zeuthen	PITZ, DESY, Zeuthen, Germany	20 MeV **electron** beam	No witness (W) beam, only D beam from RF-gun.	2015	~2017	- Study Self-Modulation Instability **(SMI)**
DESY-FLASH Forward	DESY, Hamburg, Germany	X-ray FEL type **electron** beam 1 GeV	D + W in FEL bunch. Or independent W-bunch (LWFA).	2016	2020+	- **Application (mostly) for x-ray FEL** - Energy-doubling of Flash-beam energy - Upgrade-stage: use 2 GeV FEL D beam
Brookhaven ATF	BNL, Brookhaven, USA	60 MeV **electrons**	Several bunches, D+W formed with mask.	On going		- **Study quasi-nonlinear PWFA regime.** - Study PWFA driven by multiple bunches - Visualisation with optical techniques
SPARC Lab	Frascati, Italy	150 MeV	Several bunches	On going		- Multi-purpose user facility: includes laser- and beam-driven plasma wakefield experiments

AWAKE

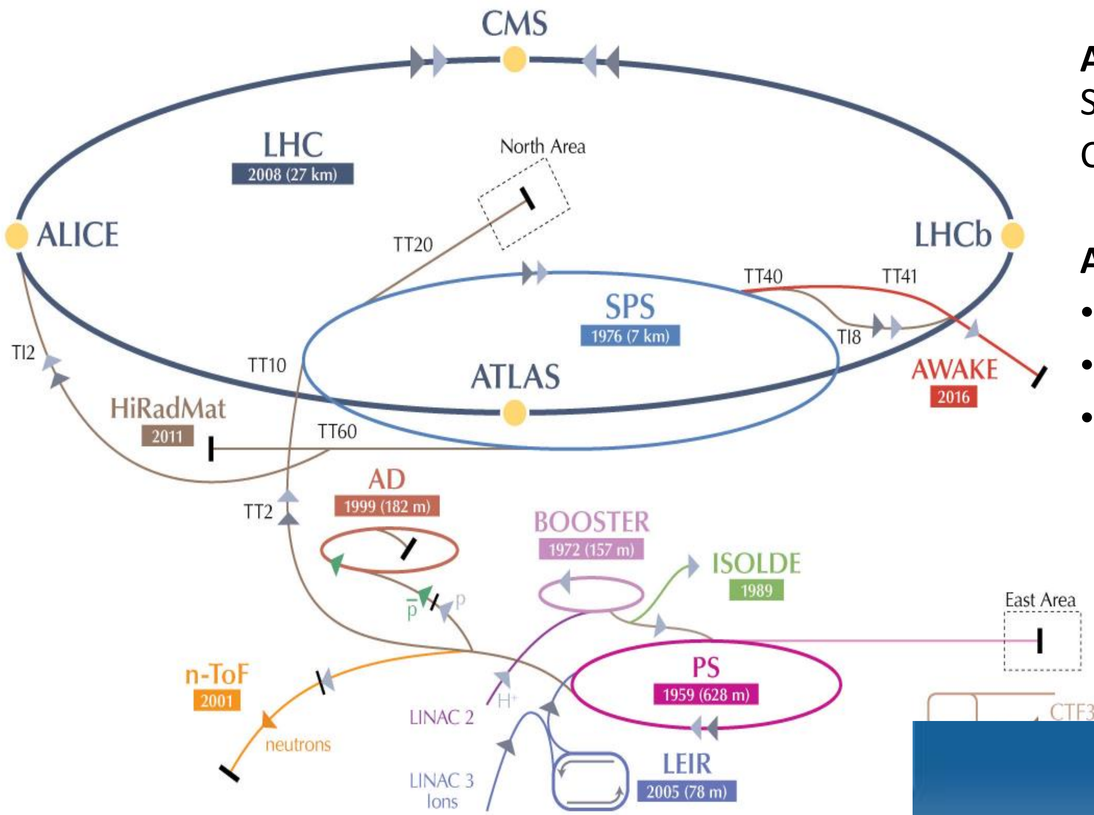
- **Advanced Proton Driven Plasma Wakefield Acceleration Experiment**
  - Final Goal: Design high quality & high energy electron accelerator based on acquired knowledge.

- Proof-of-Principle Accelerator R&D experiment at CERN
  - **First proton driven wakefield experiment worldwide**
  - Demonstration of high-gradient acceleration of electrons
  - Approved in 2013
  - First beam expected in **2016**

- AWAKE Collaboration: 16 Institutes world-wide



AWAKE at CERN

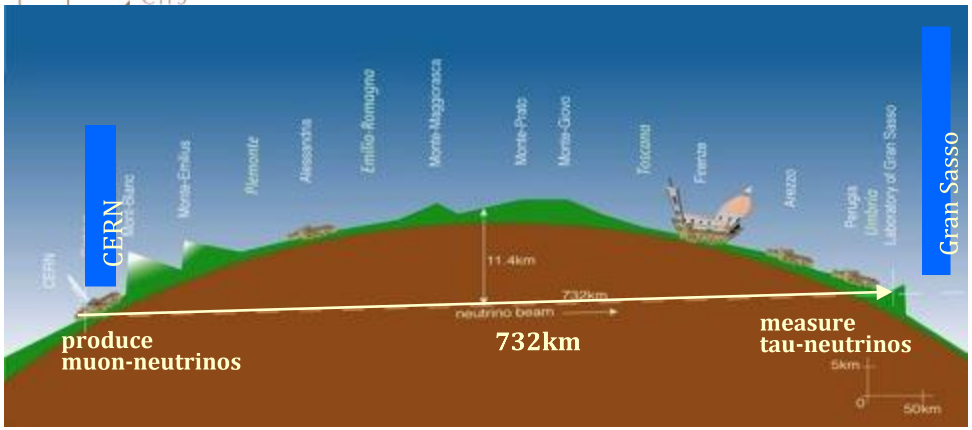


AWAKE in CNGS Facility (CERN Neutrinos to Gran Sasso)

CNGS physics program finished in 2012

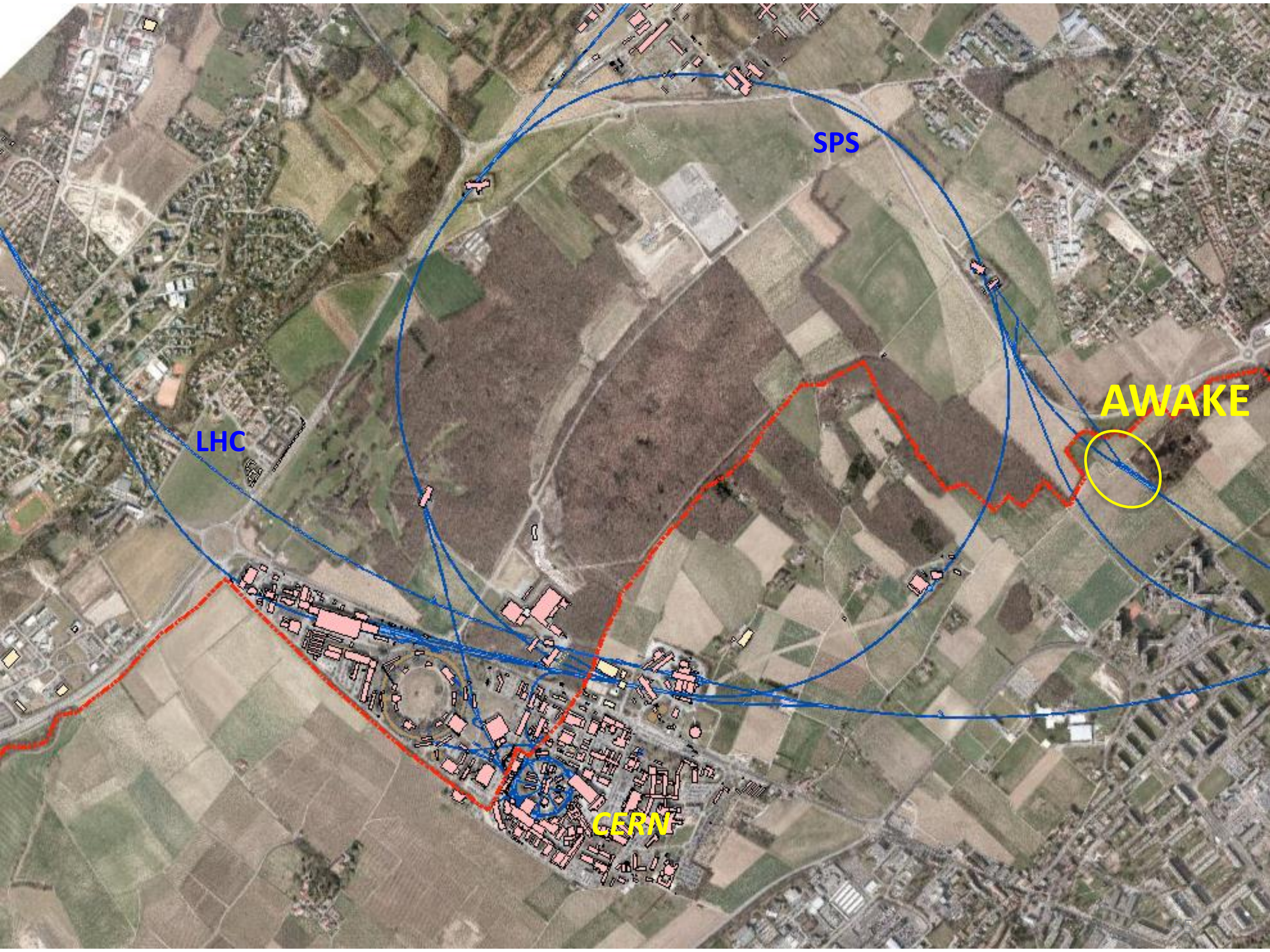
AWAKE

- Approved in August 2013
- First beam expected in 2016
- Initial program for 3-4 years

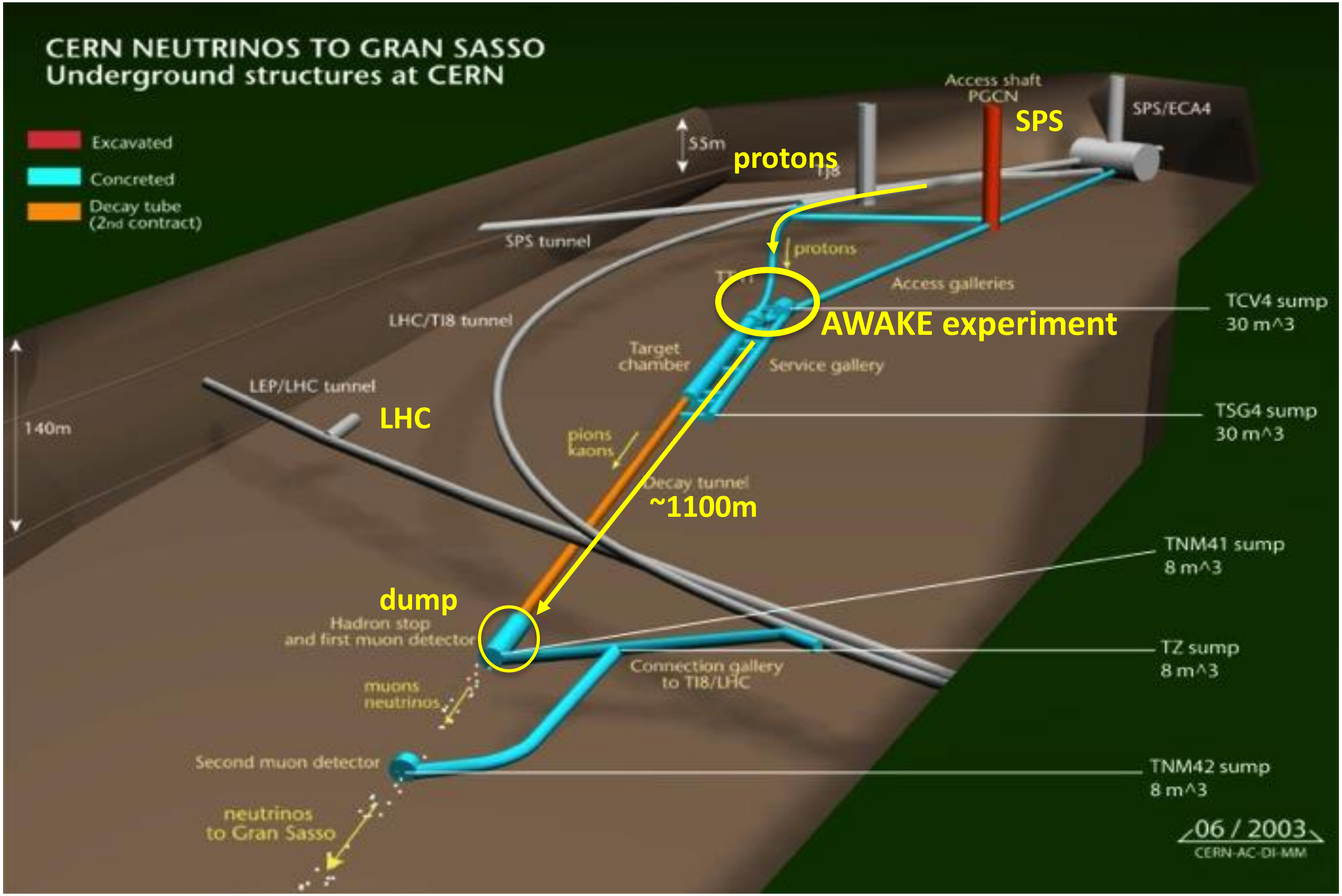


- Running underground facility
- Desired beam parameters

➔ adequate site for AWAKE

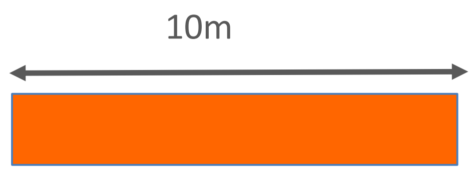

SPS
AWAKE
LHC
CERN

AWAKE at CERN



AWAKE Experimental Program

Understand **the physics of self-modulation instability** processes in plasma.



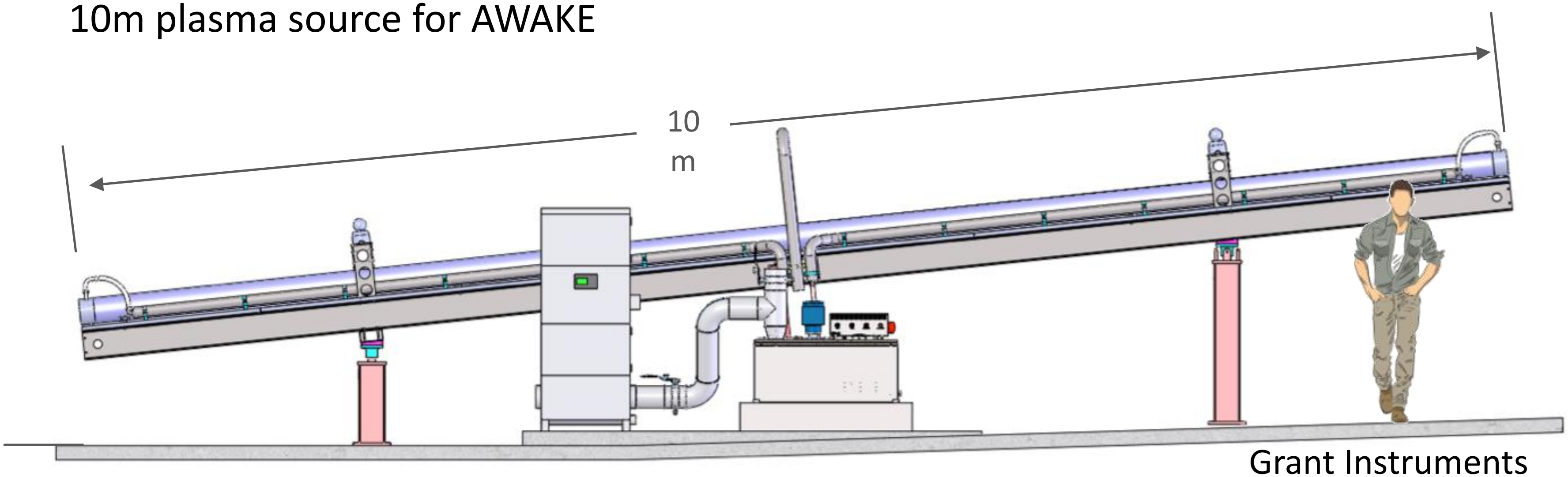
Plasma cell

→ Rb vapour source

Plasma Source: Rubidium Vapor Source

10m plasma source for AWAKE

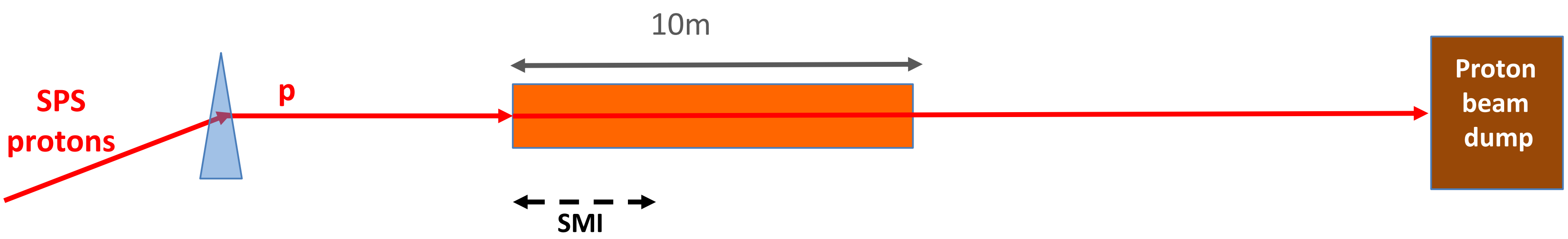
- Density adjustable from **10^{14} – 10^{15} cm^{-3}**
- 10 m long, 4 cm diameter
- Rubidium vapor
- Heated to 200 Degree



Grant Instruments

AWAKE Experimental Program

Understand **the physics of self-modulation instability** processes in plasma.



Plasma cell

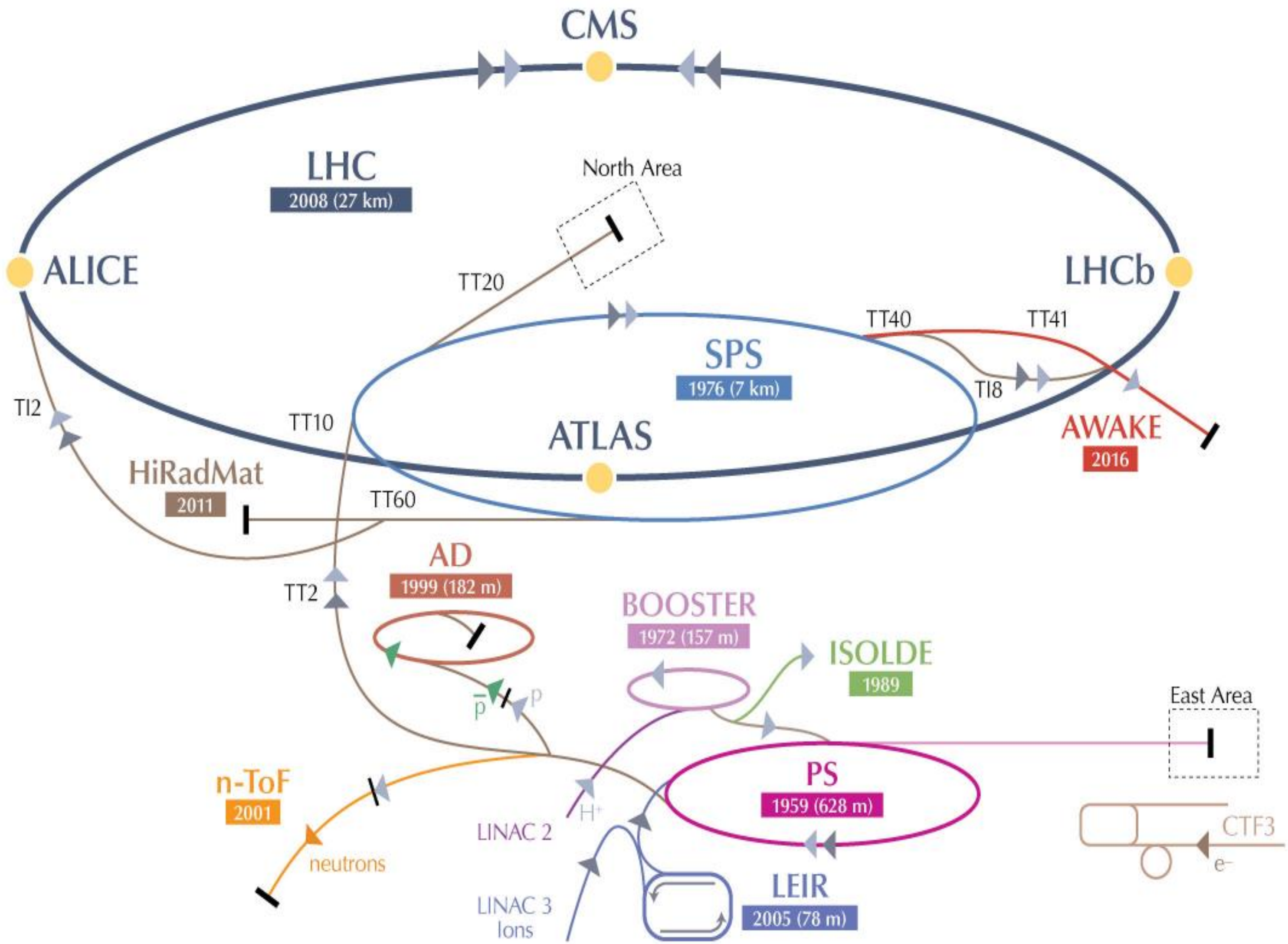
→ Rb vapour source

Proton beam

→ drives the plasma wakefield + undergoes self-modulation instability.

→ LHC-type proton beam, 400 GeV/c, 3E11 protons/bunch, 400ps long

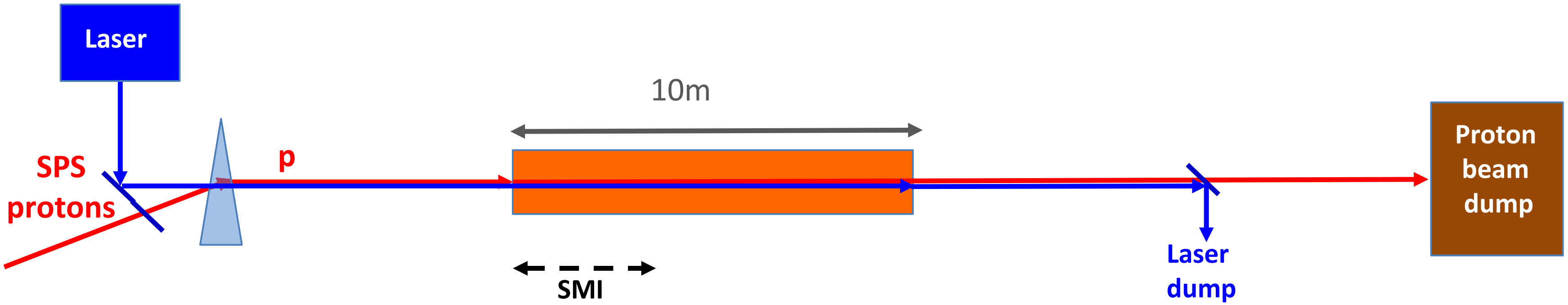
Proton Beam



CMS
LHC
2008 (27 km)
North Area
ALICE
TT20
LHCb
TT40
TT41
SPS
1976 (7 km)
TI8
TI2
TT10
ATLAS
AWAKE
2016
HiRadMat
2011
TT60
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
p̄
p
East Area
n-ToF
2001
PS
1959 (628 m)
H+
LINAC 2
CTF3
e–
neutrons
LINAC 3
Ions
LEIR
2005 (78 m)

AWAKE Experimental Program

Understand **the physics of self-modulation instability** processes in plasma.



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→ drives the plasma wakefield + undergoes self-modulation instability.

→ LHC-type proton beam, 400 GeV/c, 3E11 protons/bunch, 400ps long

Laser beam:

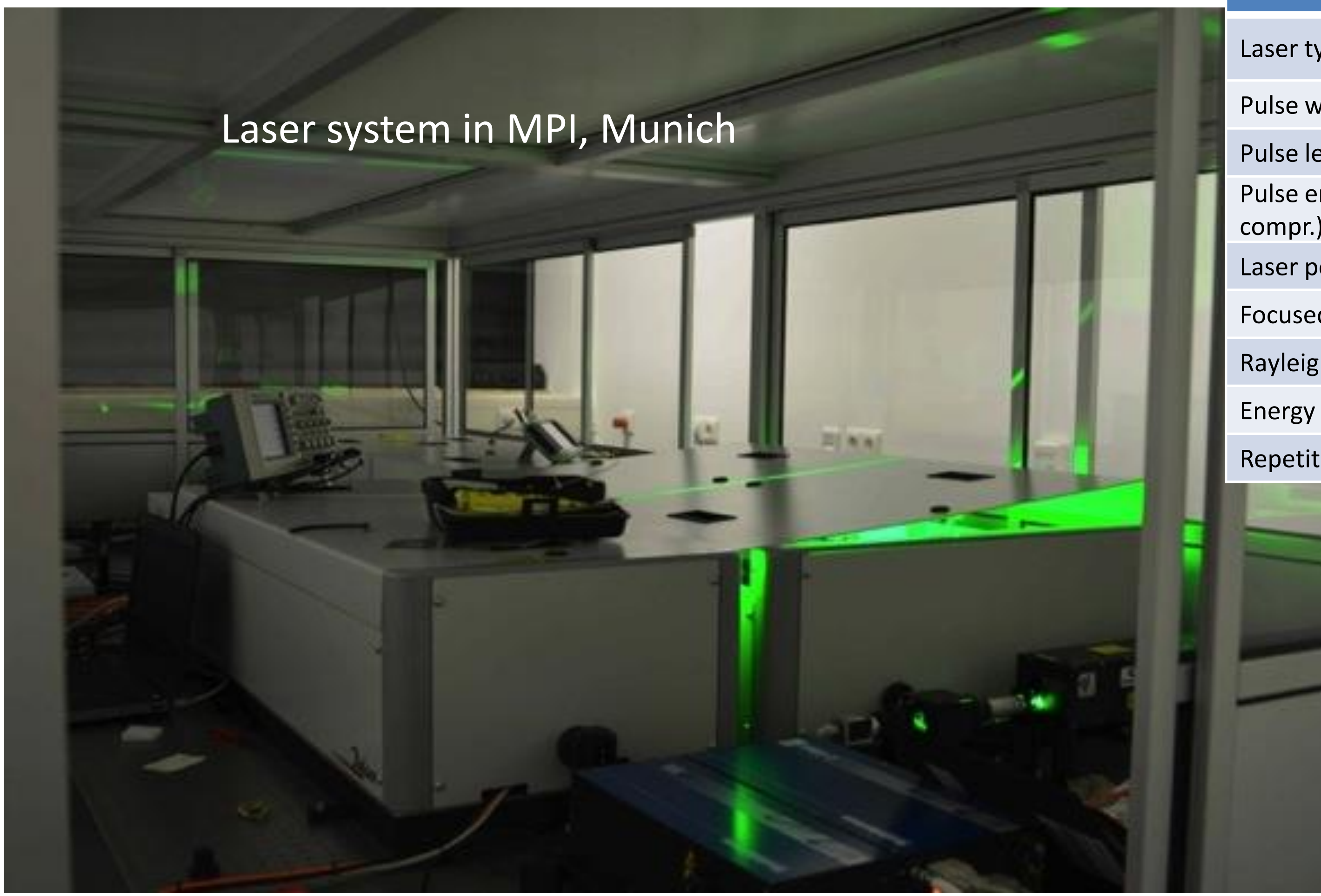
→ ionizes the plasma + seeds the self-modulation instability of the proton beam.

→ 4.5TW laser, 100fs

Laser

- Laser intensity must exceed ionization intensity at the plasma end (L=10m) over a plasma radius of $r > 3\sigma = 600\ \mu m$.

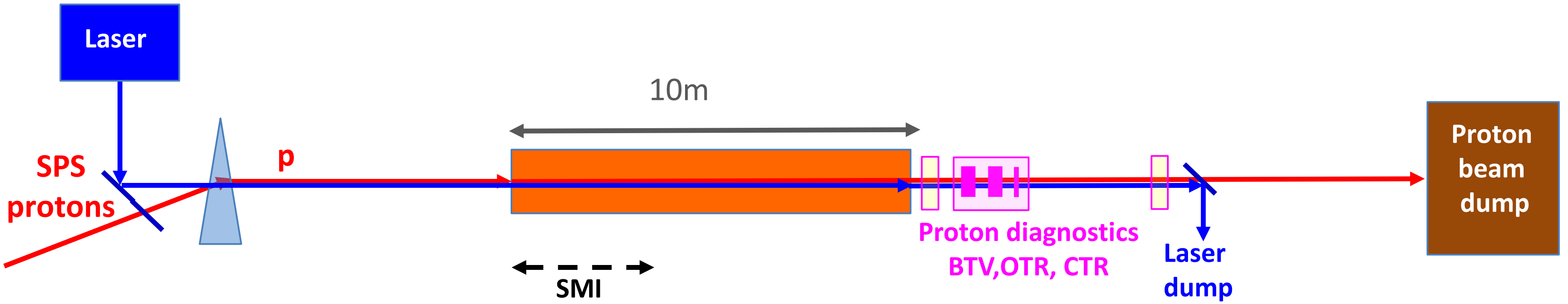
Laser Beam	
Laser type	Fiber Ti:Sapphire
Pulse wavelength	λ_0 = 780 nm
Pulse length	100-120 fs
Pulse energy (after compr.)	**450 mJ**
Laser power	4.5 TW
Focused laser size	$\boldsymbol{\sigma_{x,y}}$ **= 1 mm**
Rayleigh length Z_R	5 m
Energy stability	±1.5% r.m.s.
Repetition rate	10 Hz



➔ 4.5 TW Laser for ionization and seeding

AWAKE Experimental Program

Understand **the physics of self-modulation instability** processes in plasma.



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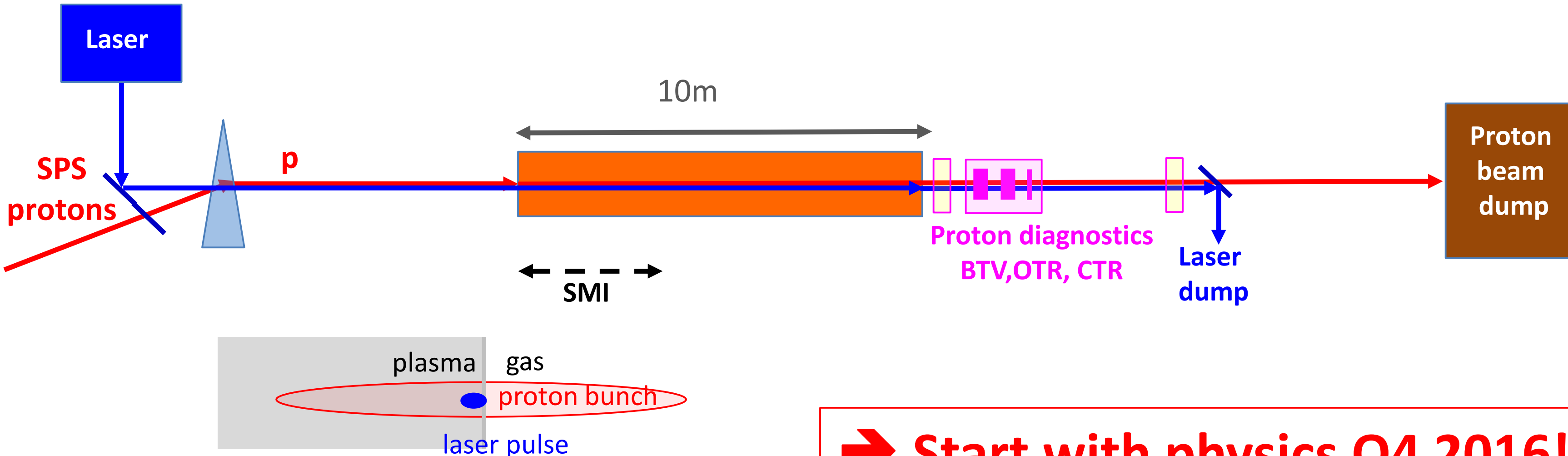
→ 4.5TW laser, 100fs

Diagnostics

→ BTVs, OTR, CTR

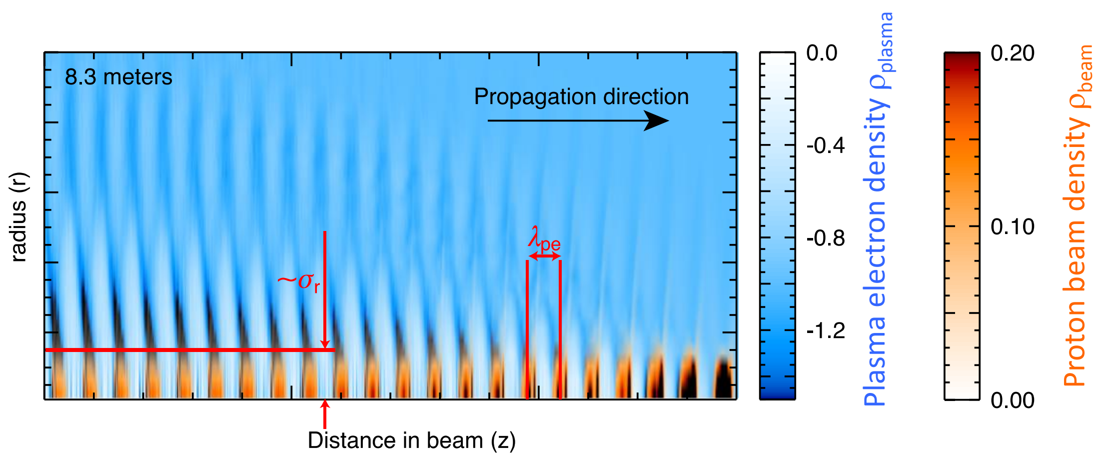
AWAKE: Experimental Program

Understand **the physics of self-modulation instability** processes in plasma.



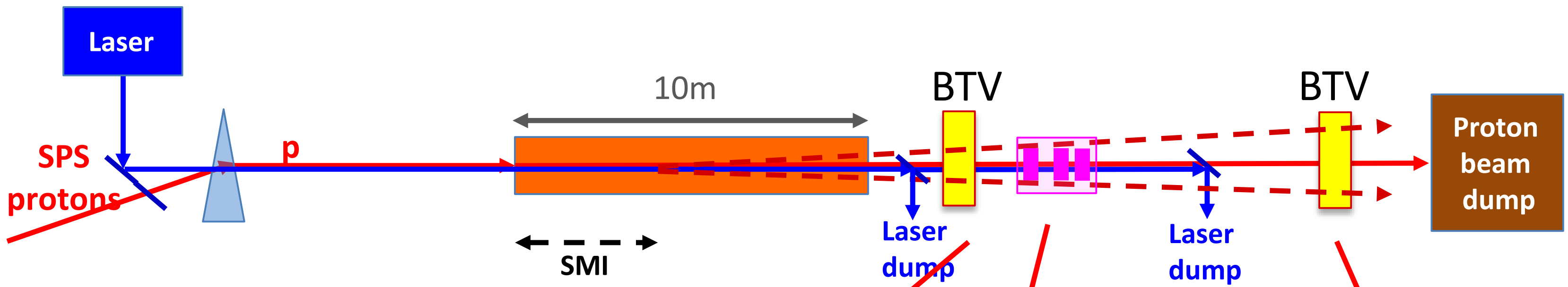
➔ **Start with physics Q4 2016!!**

Self-modulated proton bunch resonantly driving plasma wakefields.

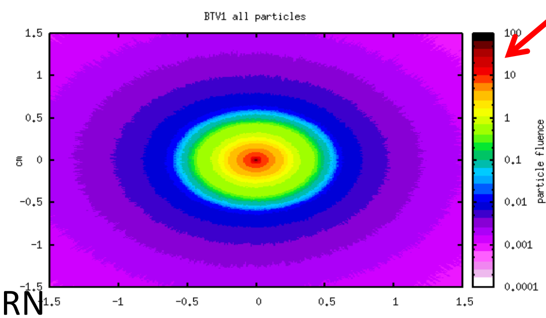


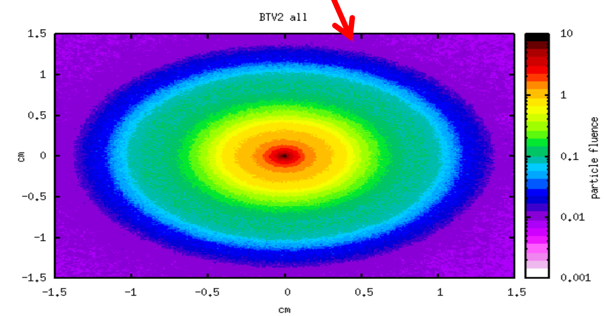
J. Vieira et al PoP 19063105 (2012)

Drive Beam Diagnostics



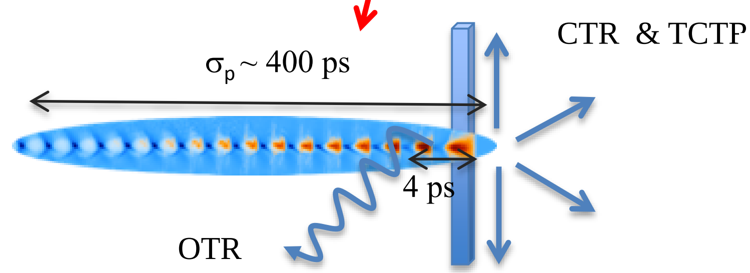
Indirect SMI Measurement: Defocusing of the proton beam

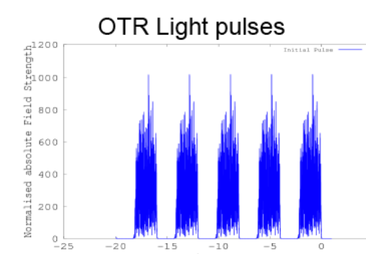




M. Turner, A. Petrenko, CERN

Direct SMI Measurement: Radiation emitted by bunch when traversing dielectric material
→ Streak camera

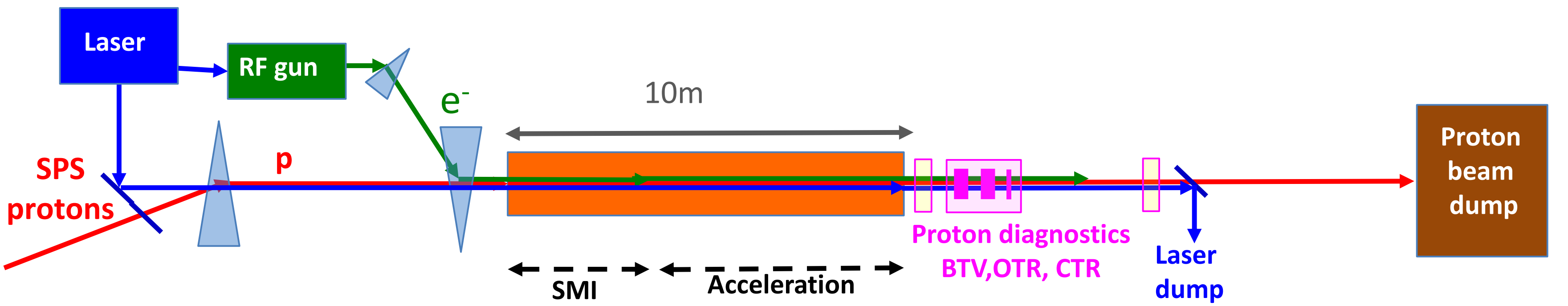




K. Rieger, P. Muggli, MPI

AWAKE Experimental Program

- Understand **the physics of self-modulation instability** processes in plasma.
- **Probe the accelerating wakefields** with externally injected electrons.



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Laser beam:

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→ 4.5TW laser, 100fs

Diagnostics

→ BTVs, OTR, CTR

Electron source and beam

→ Witness beam to 'surf' on the wakefield and get accelerated

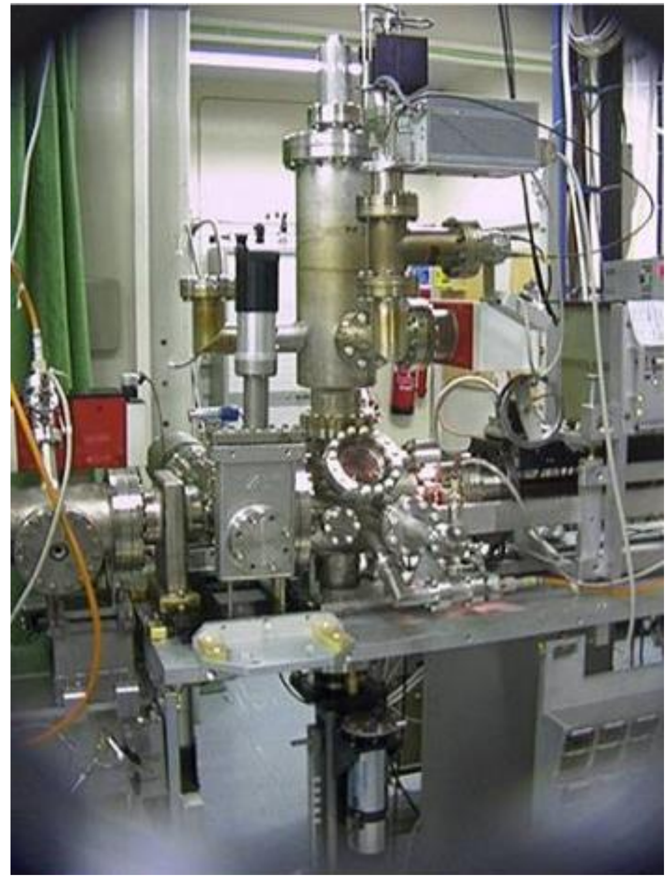
→ 16 MeV/c, 1.29 electrons/ bunch, 4ps long

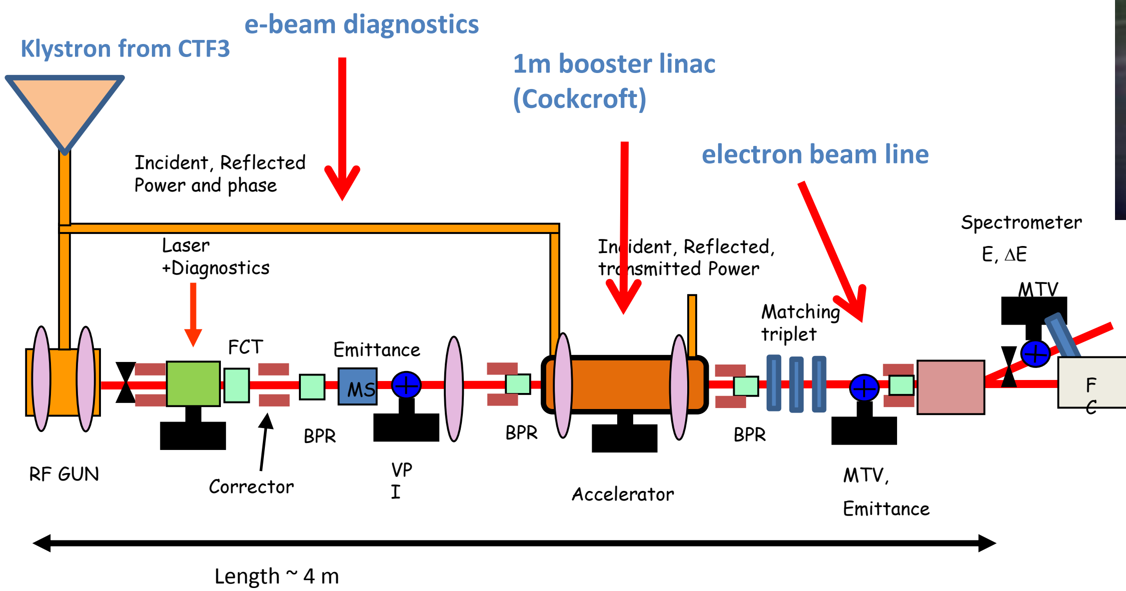
4. Witness Beam: Electron Source

PHIN Photo-injector for CTF3/CLIC:

- Charge/bunch: 2.3 nC
- Bunch length: 10 ps
- 1800 bunches/train, 1.2μs train-length
- → Program will stop end 2015

→ Fits to requirements of AWAKE





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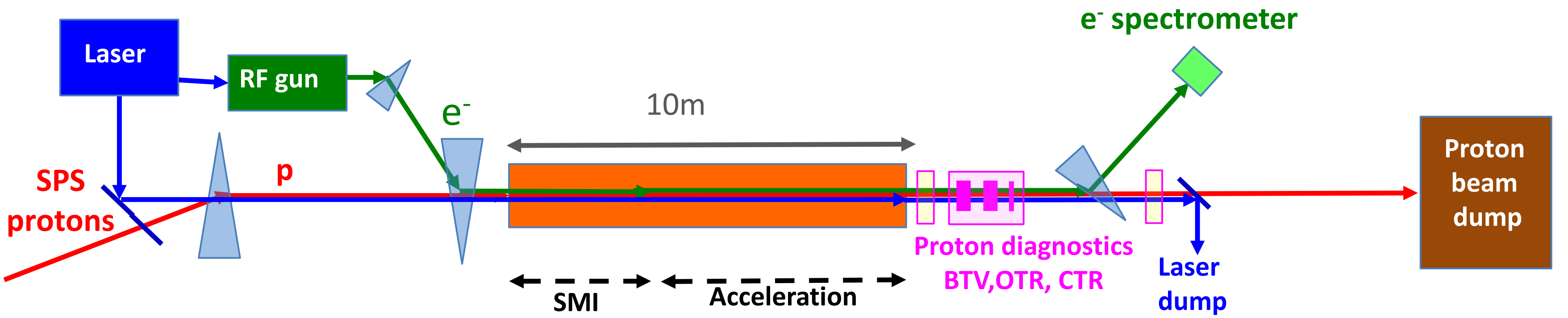

→ Start with physics Q4 2017!!

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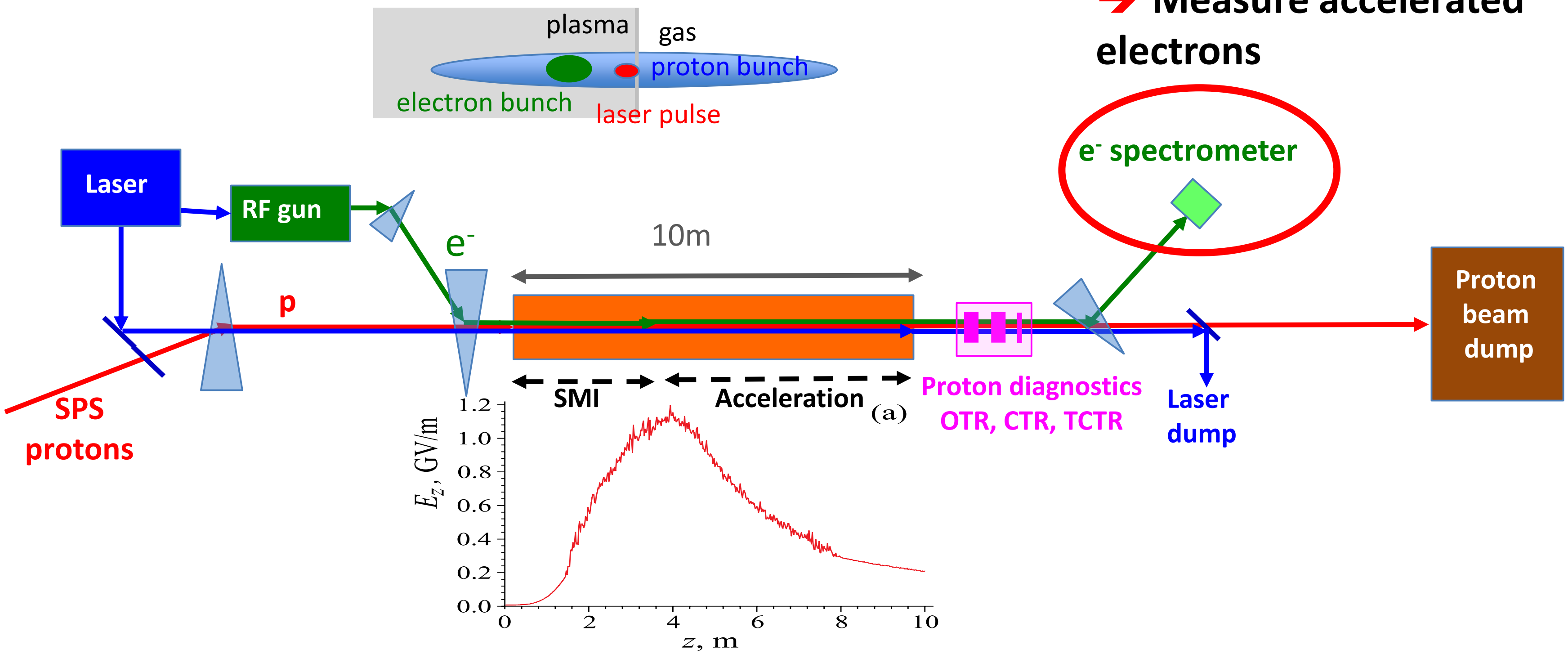
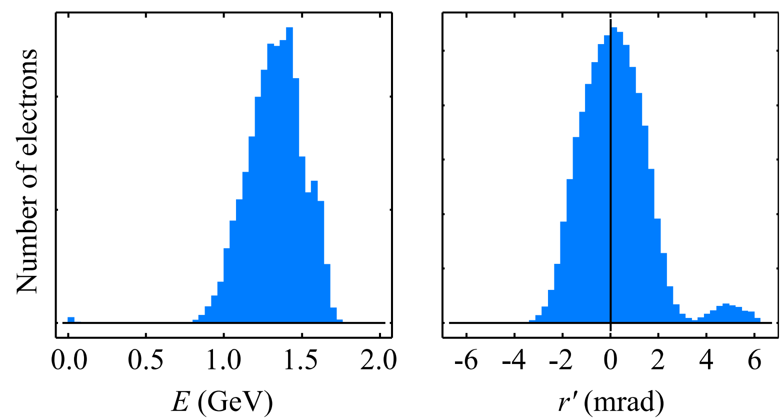
→ Witness beam to 'surf' on the wakefield and get accelerated
→ 16 MeV/c, 1.29 electrons/ bunch, 4ps long

Electron spectrometer system

AWAKE Experiment: 2nd Phase

➔ **Measure accelerated electrons**



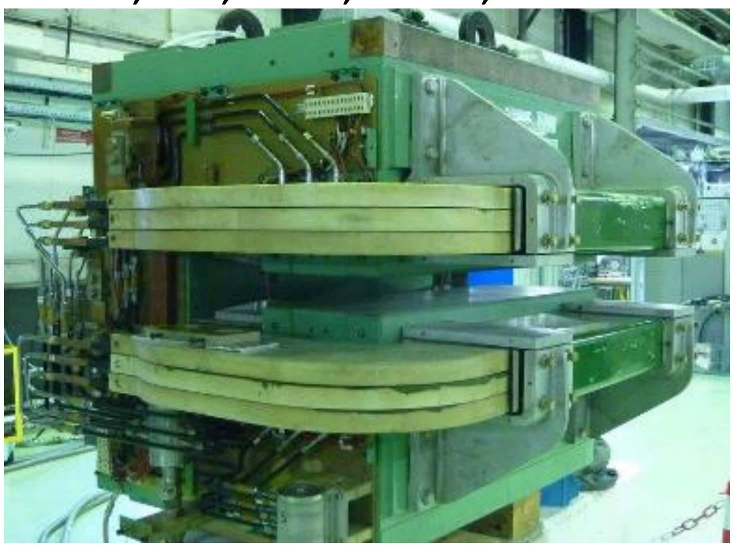


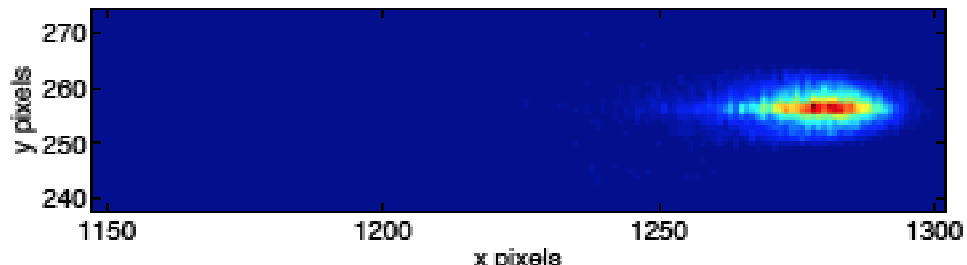
- Trapping efficiency: 10 – 15 %
- Average energy gain: 1.3 GeV
- Energy spread: $\pm$ 0.4 GeV
- Angular spread up to $\pm$ 4 mrad

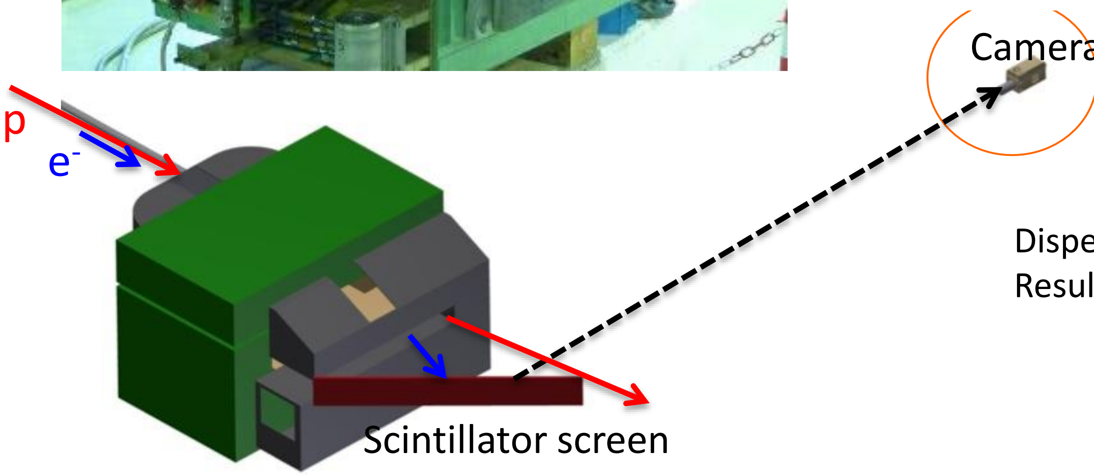
5. Witness Beam Acceleration Diagnostics

Probe the accelerating wakefields with externally injected electrons → Electron spectrometer

8.5 ton, 1.2 T, 1.3 Tm, L=1.6 m, W=1.3 m

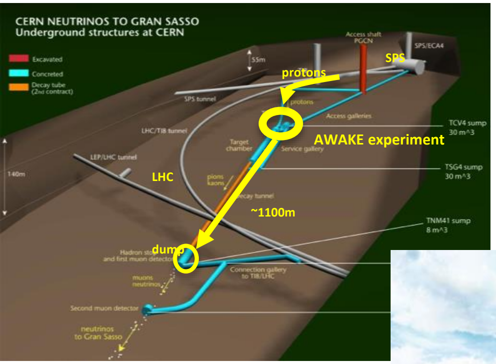


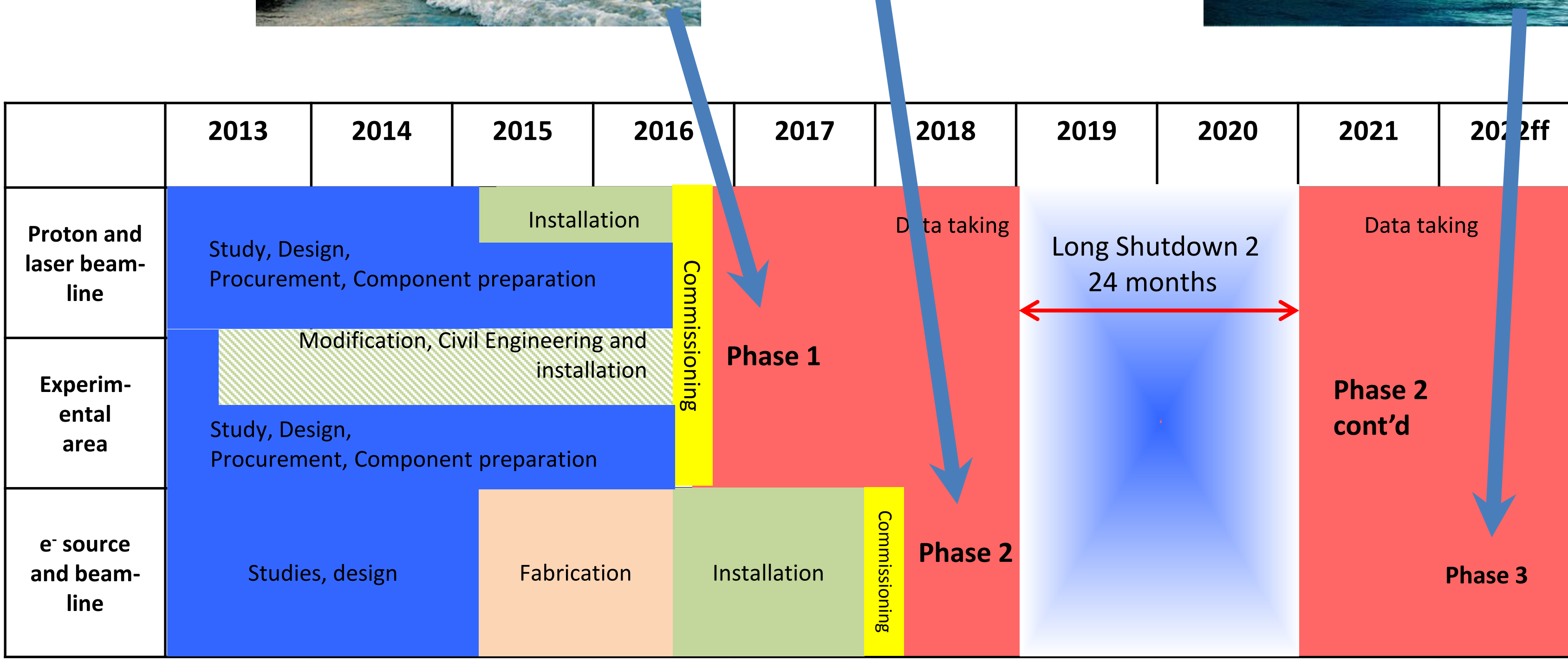




Dispersed electron impact on scintillator screen.
Resulting light collected with intensified CCD camera.

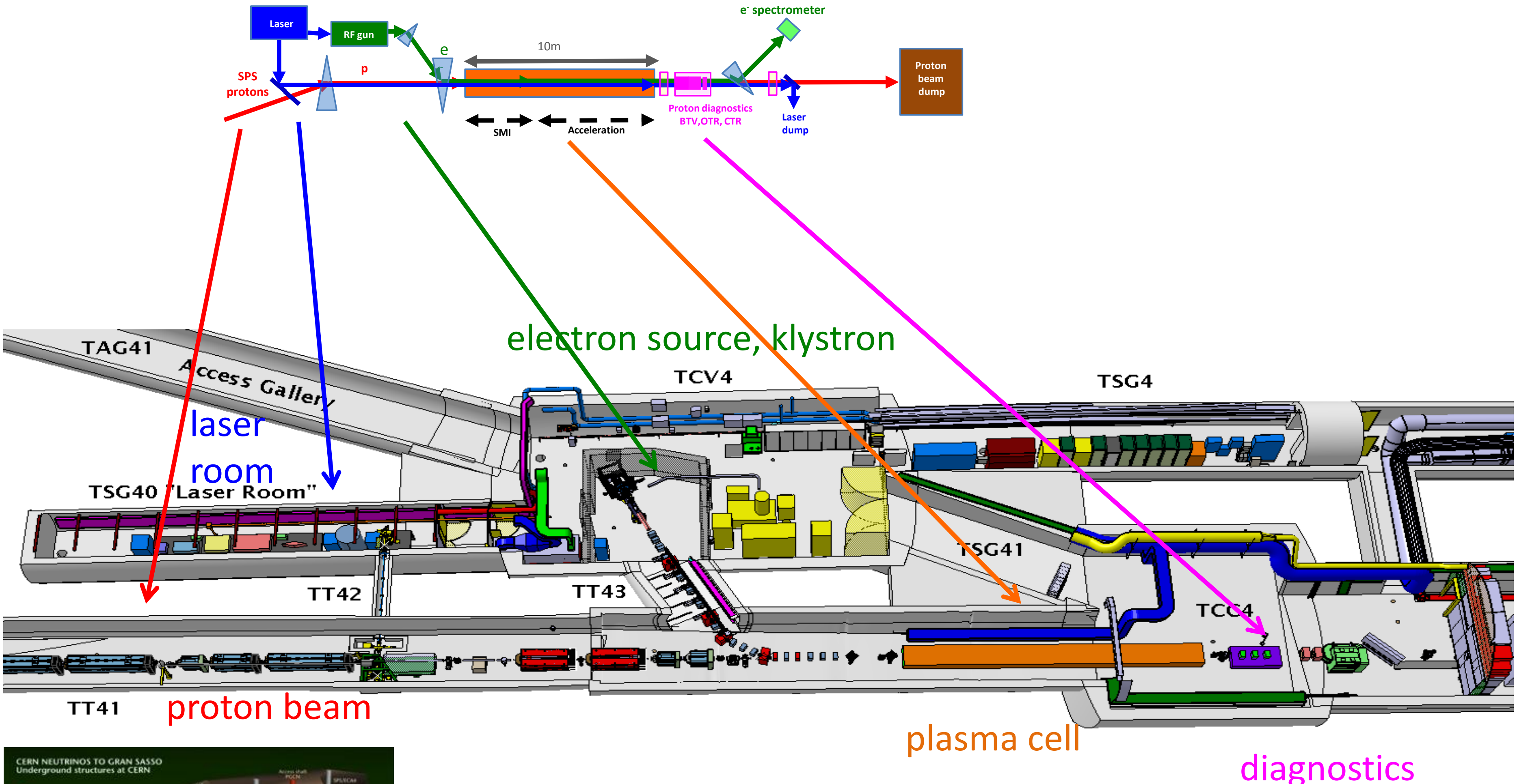
AWAKE Time Line

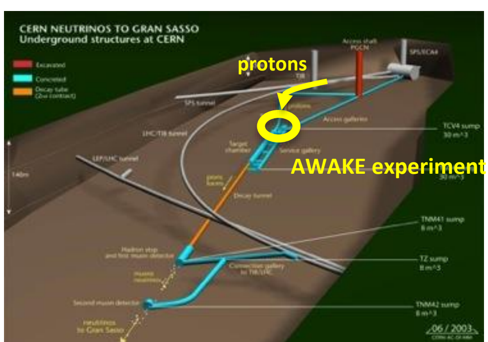




The AWAKE Area Preparation

AWAKE Experimental Facility





Proton Beam Line

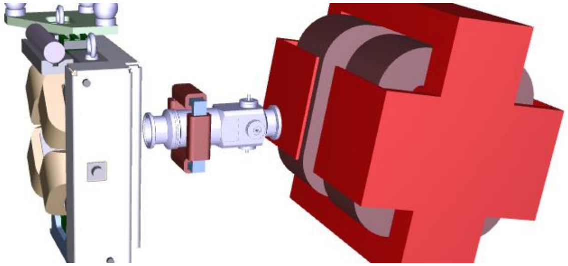
Proton beam line from SPS extraction to ~80 m upstream the AWAKE facility stays untouched.

Proton Line close just Upstream the Plasma

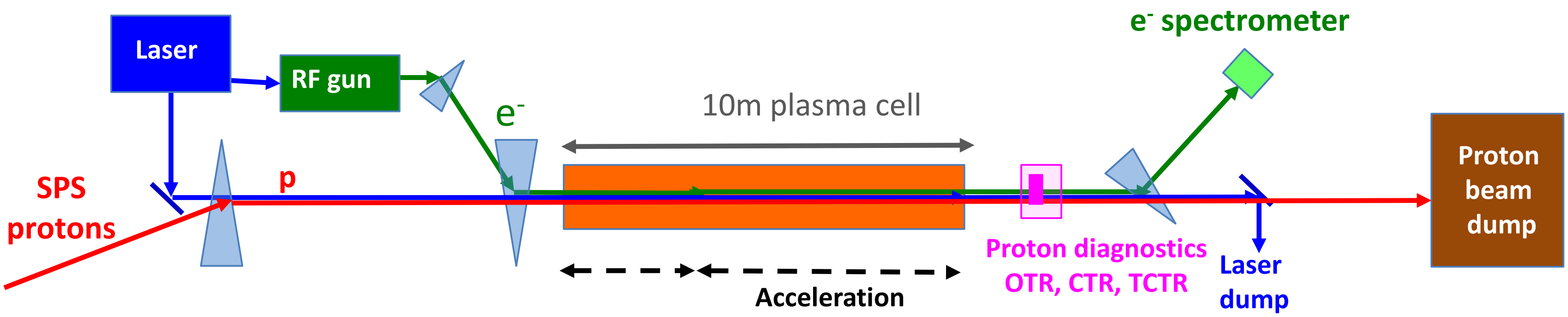
Laser Room

Electron Beam Tunnel Excavation

Electron Beam Line Tunnel



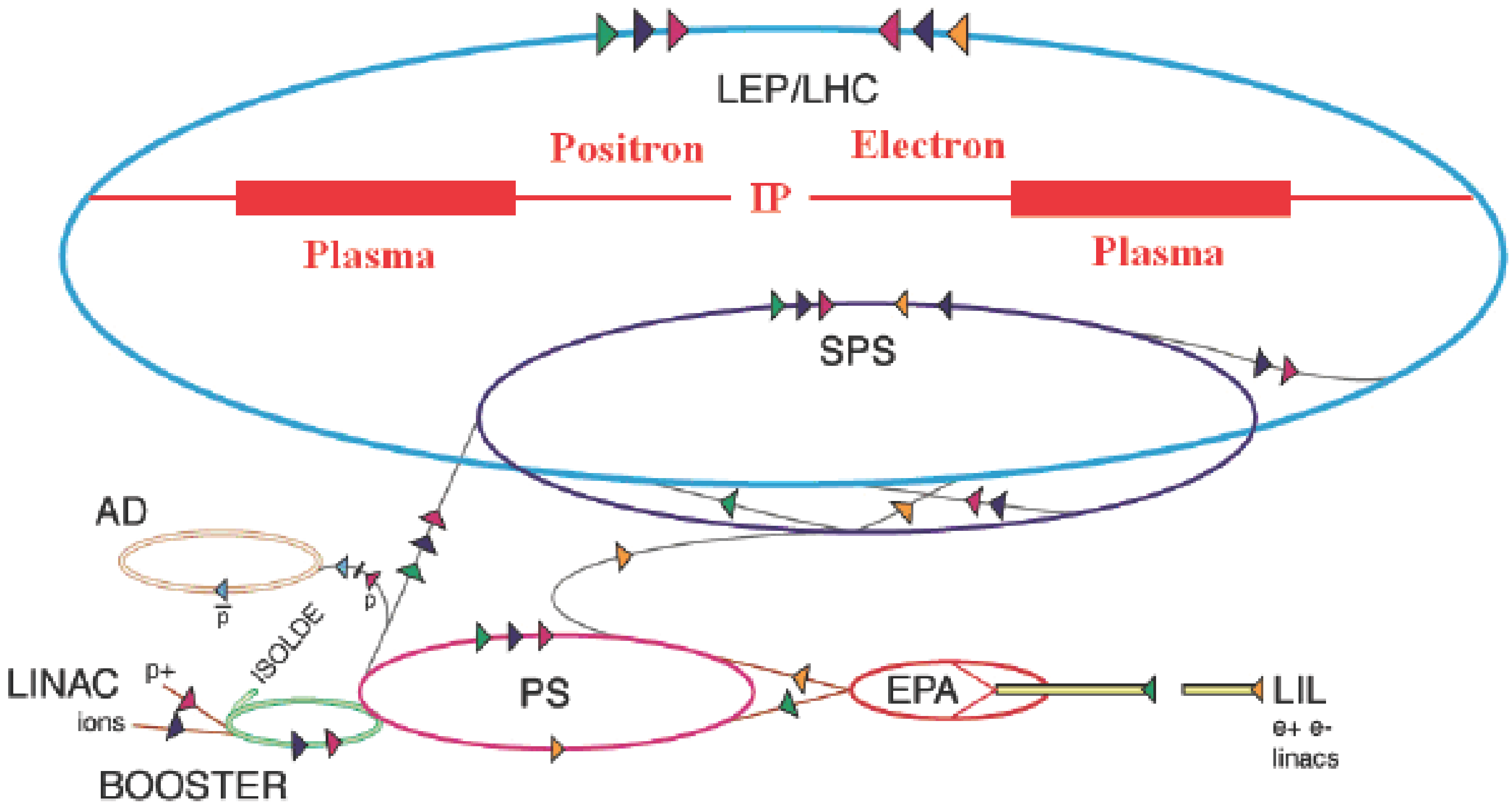
The AWAKE Experiment at CERN



- **AWAKE is proof-of-concept experiment with the aim to provide a design for a high energy physics frontier accelerator.**

- Experimental Program
  - Perform **benchmark experiments using proton bunches** to drive wakefields for the first time ever.
  - Understand **the physics of self-modulation instability** processes in plasma. ➔ **Q4 2016**
  - **Probe the accelerating wakefields with externally injected electrons**, including energy spectrum measurements for different injection and plasma parameters. ➔ **Q4 2017**
  - **Develop long scalable and uniform plasma** cells, production of **shorter electron and proton bunches** (2020) ➔ **2021ff**

The Future



G. Xia et al, NIMA 740 (2014)173-179