

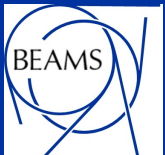


Secondary Beams provided to the Experiments

Beamline for Schools 2023

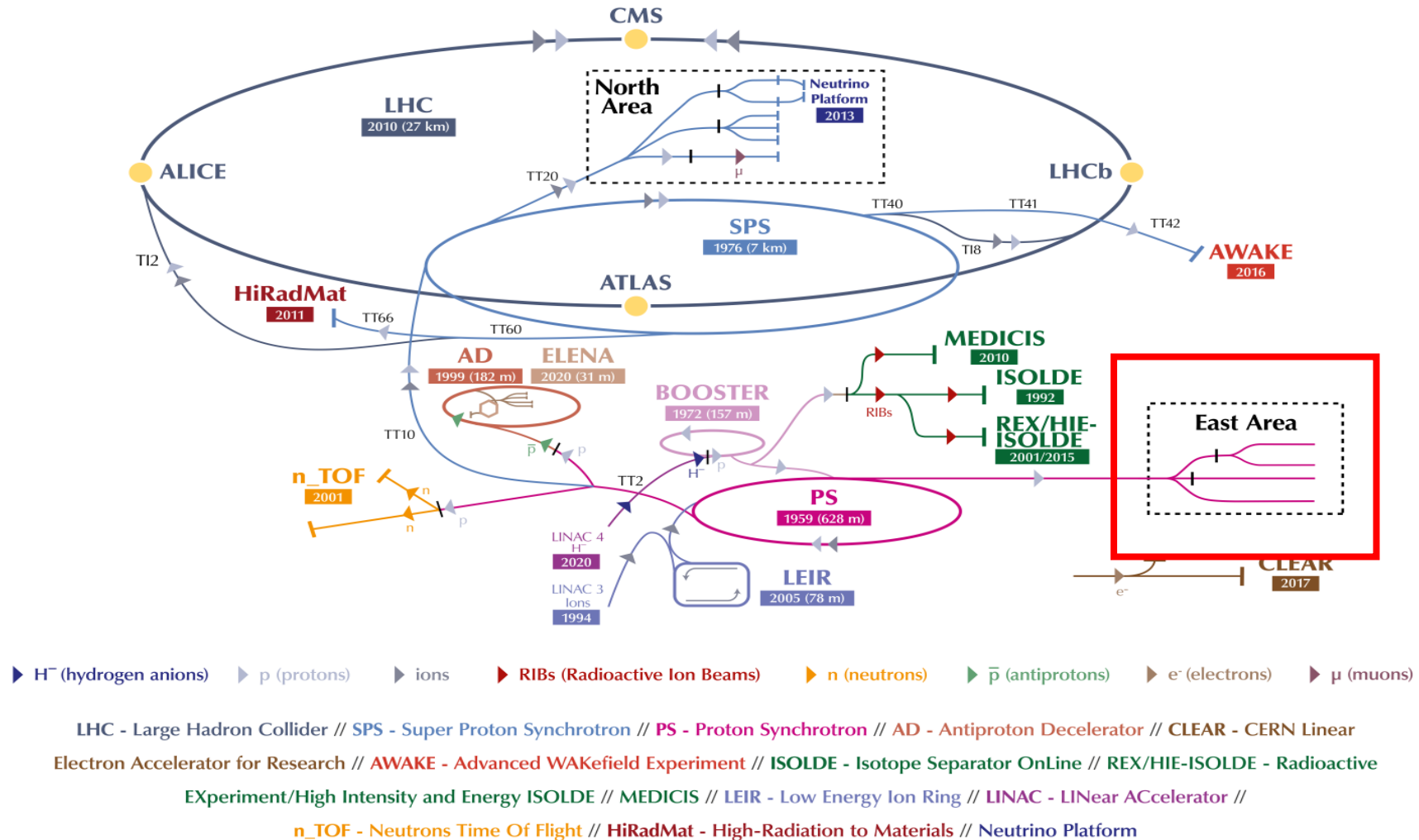
L. Nevay, M. Van Dijk, D. Banerjee, J. Bernhard (BE-EA-LE)

Date: 16.09.2023



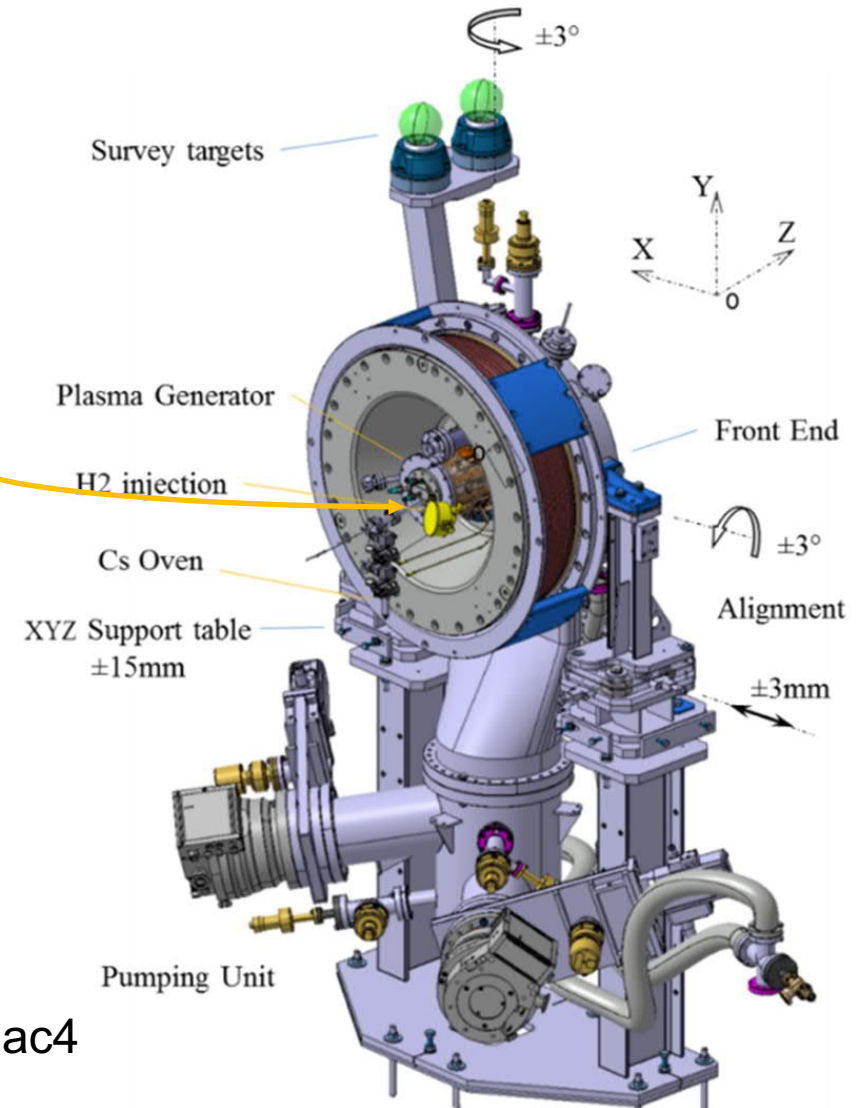
Overview

The CERN accelerator complex *Complexe des accélérateurs du CERN*



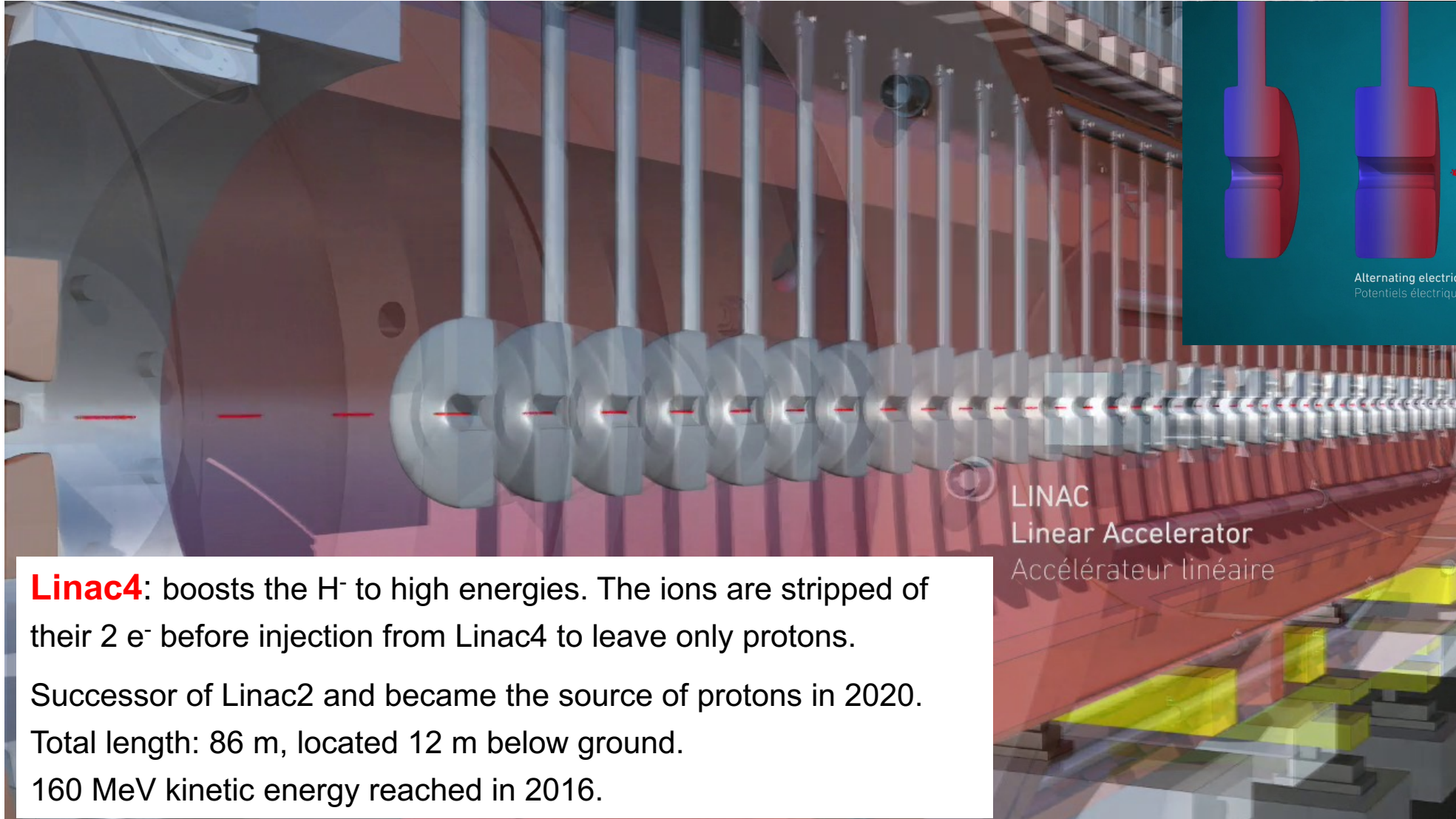
January 2021

Where does the beam come from?



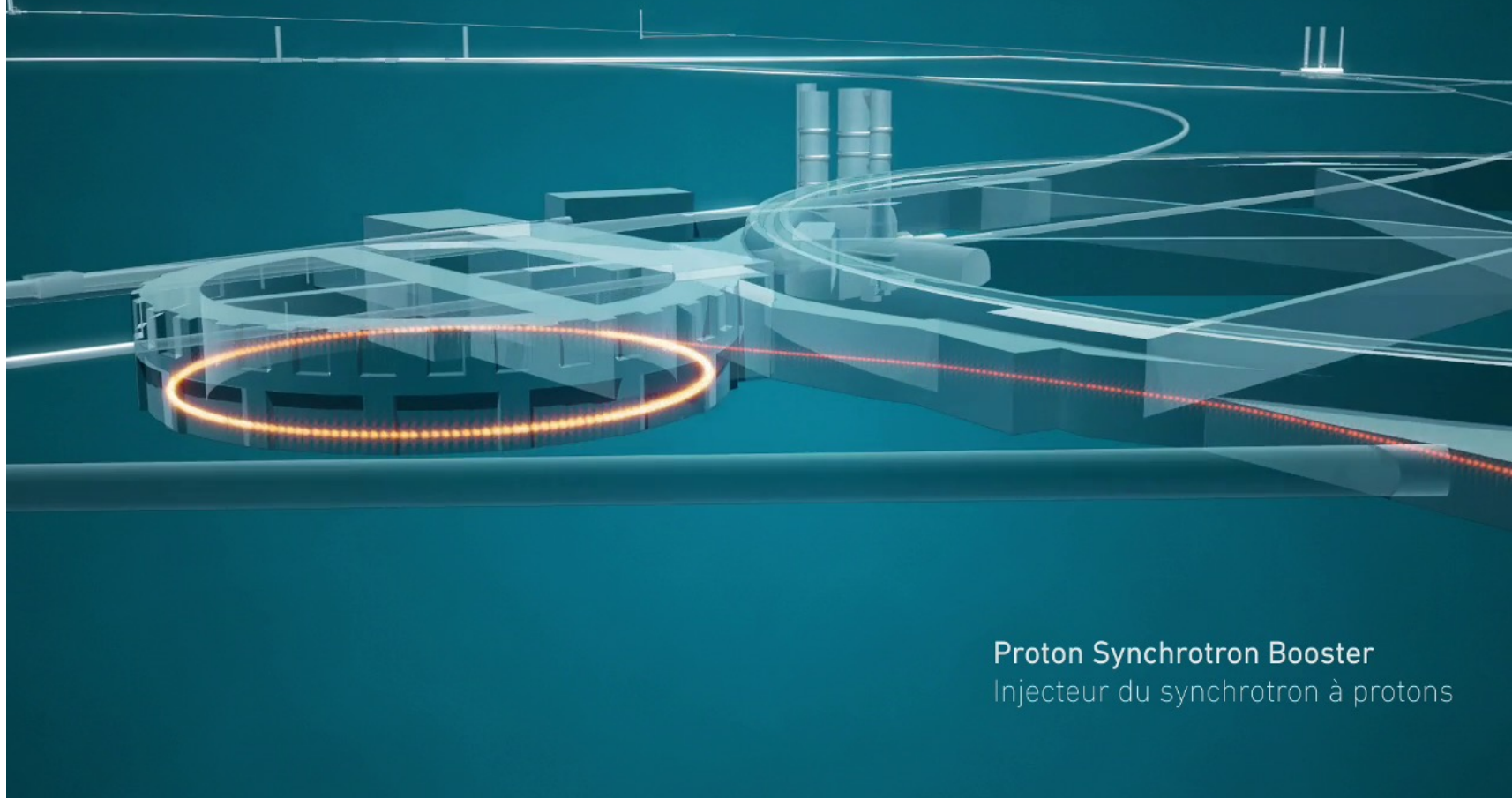
H⁻ ion source for Linac4

Where does the beam come from?



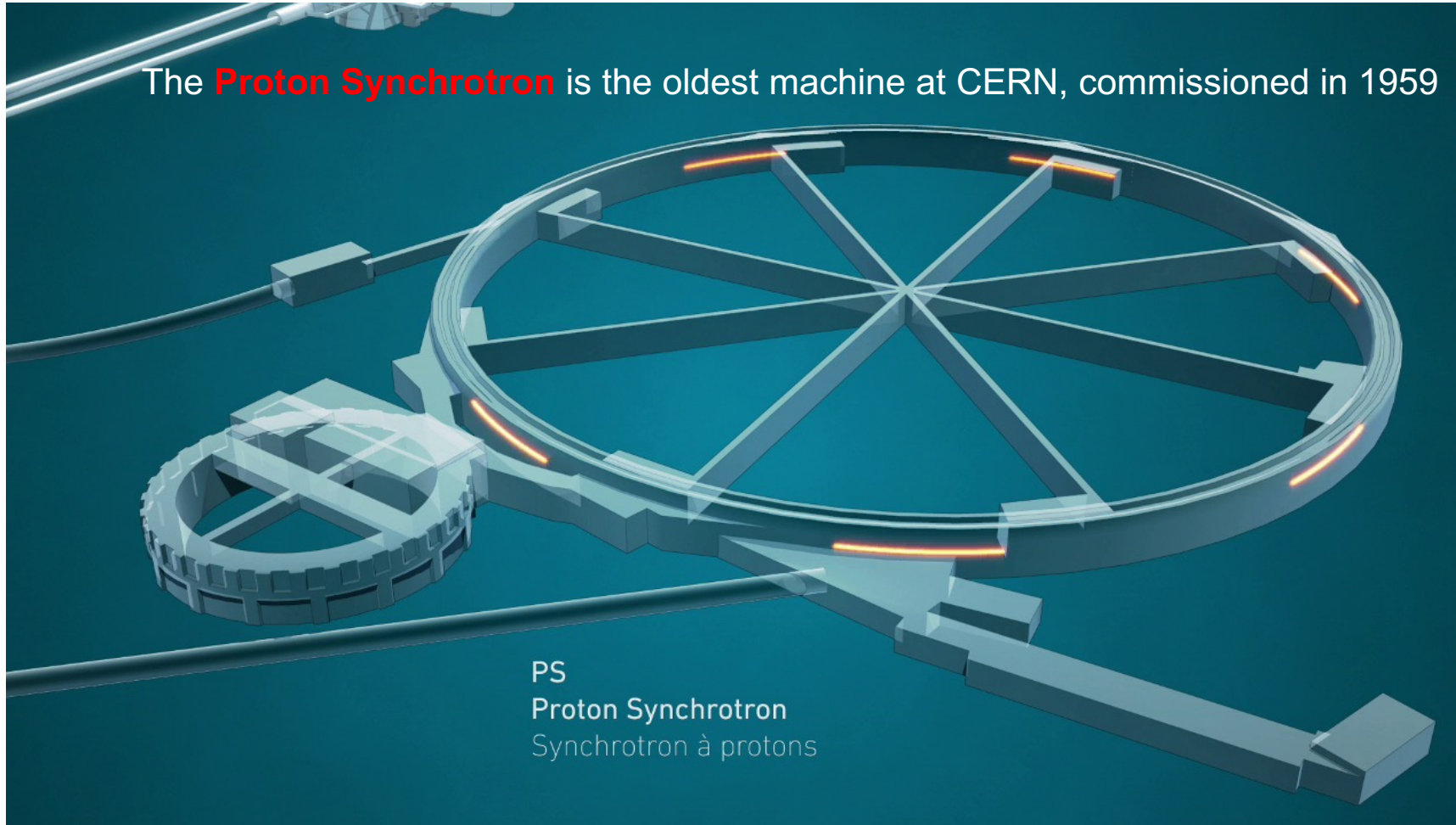
Where does the beam come from?

The **PS Booster** was built in 1972, its circumference is ~157 metres (1/4 x PS).



- The PSB receives the beam from Linac4 and accelerates it to 2 GeV/c for injection into the PS.
- It consists of 4 parallel rings, which can be operated rather independently, e.g., 1 ring for the East Area and 1 for nTOF.
- The PSB cycle is 1.2 seconds. The intensity spans 4 orders of magnitude, up to 3.2×10^{13} .

Where does the beam come from?

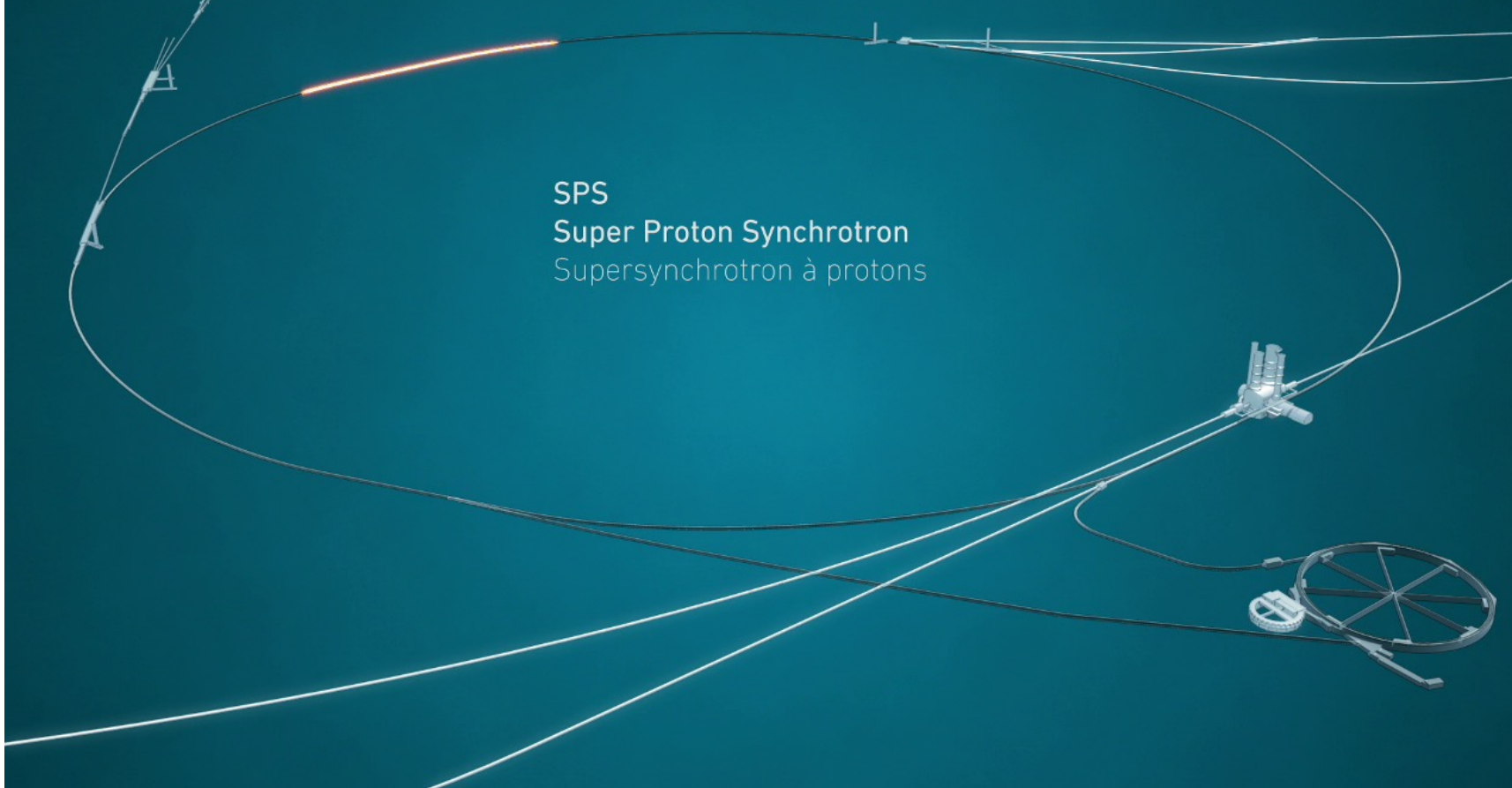


- The PS is still functioning well and even well beyond its initial specifications.
- The PS has a circumference of ~628 m and is capable to accelerate protons up to 26 GeV/c.
- Contrary to the SPS, the PS has no separate quadrupoles, but it has shaped pole faces and special coils in the main magnet units to provide the focusing. In total there are 100 main magnets and as many straight sections with special function equipment.

The PS cycle is 1.2 seconds. The PS serves many users, including the SPS North Area, the LHC, the AD, the East Area, nTOF and machine studies.

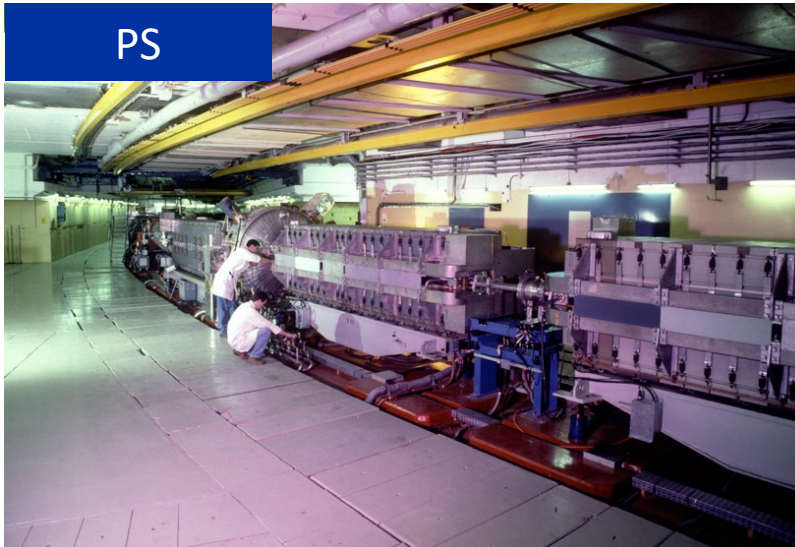
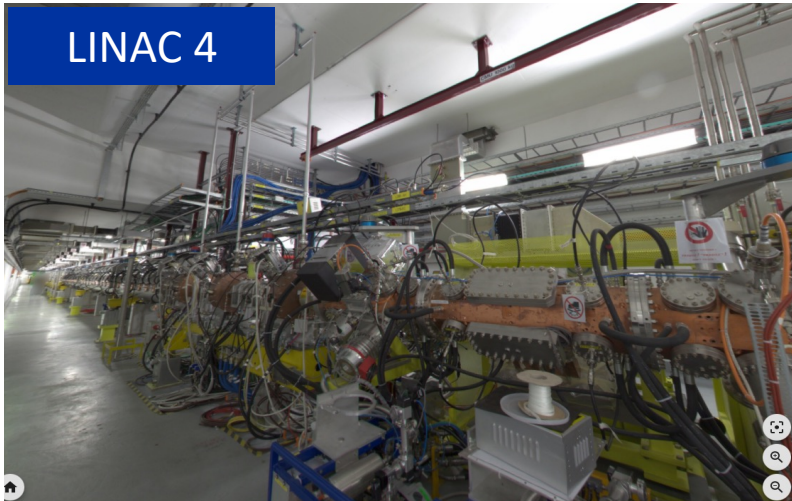
Where does the beam come from?

The **Super Proton Synchrotron** is the last accelerator in the injector chain before the LHC.

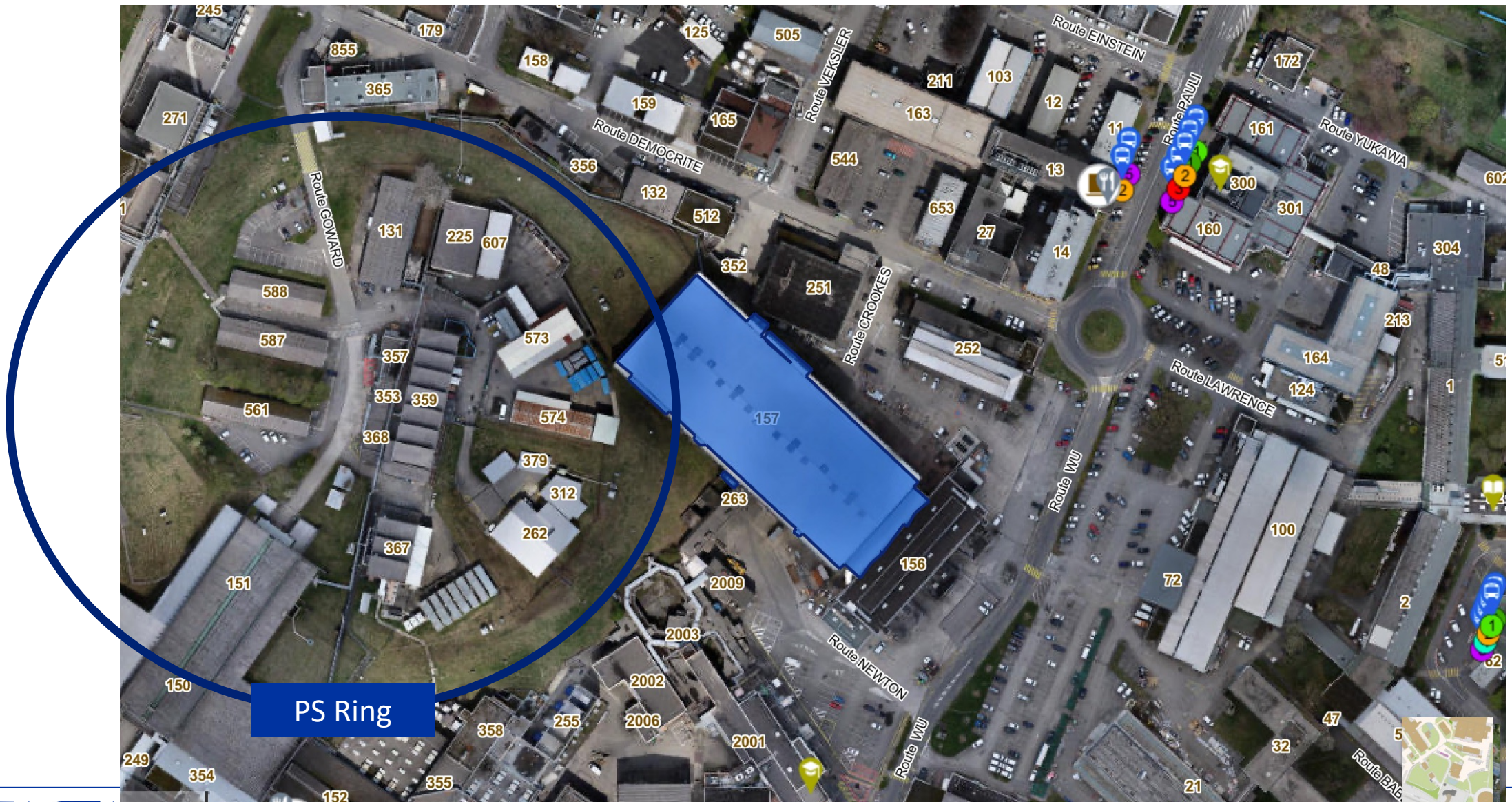


- The SPS commissioning started in 1976, but the North Experimental Area started only in 1978.
- Originally designed for fixed target proton operation at 300 GeV/c, it has operated up to 450 GeV/c for fixed target physics (and LHC filling), but also as a prestigious p-pbar collider (270 GeV/c) and as injector for LEP. It has also served the heavy ion physics programs with various ion species, up to Pb.
- The circumference of the SPS is 11 times the PS: about 6.9 km ($t_{\text{rev}} = 23$ ms).

Some pictures



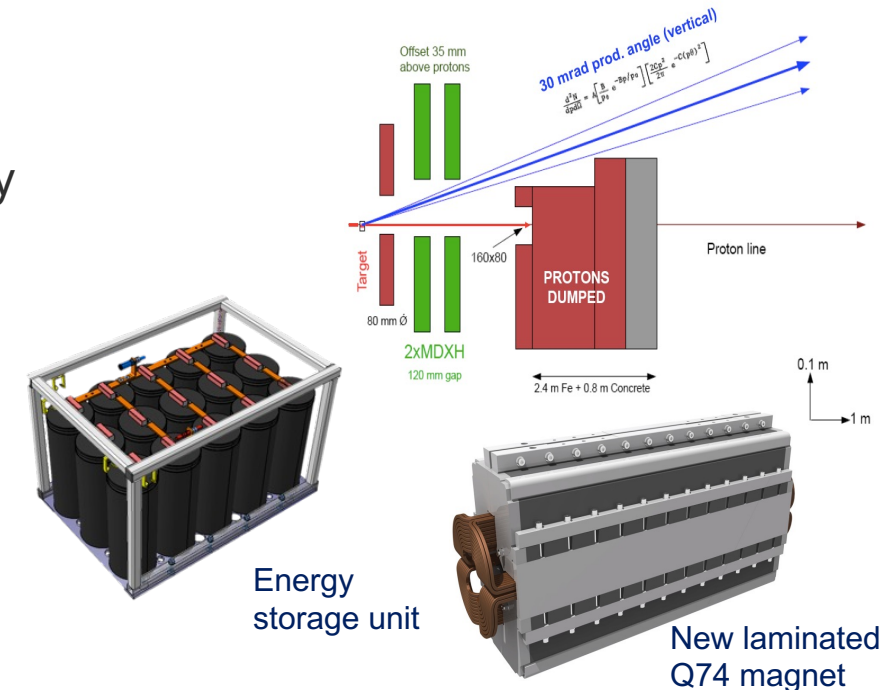
The East Area



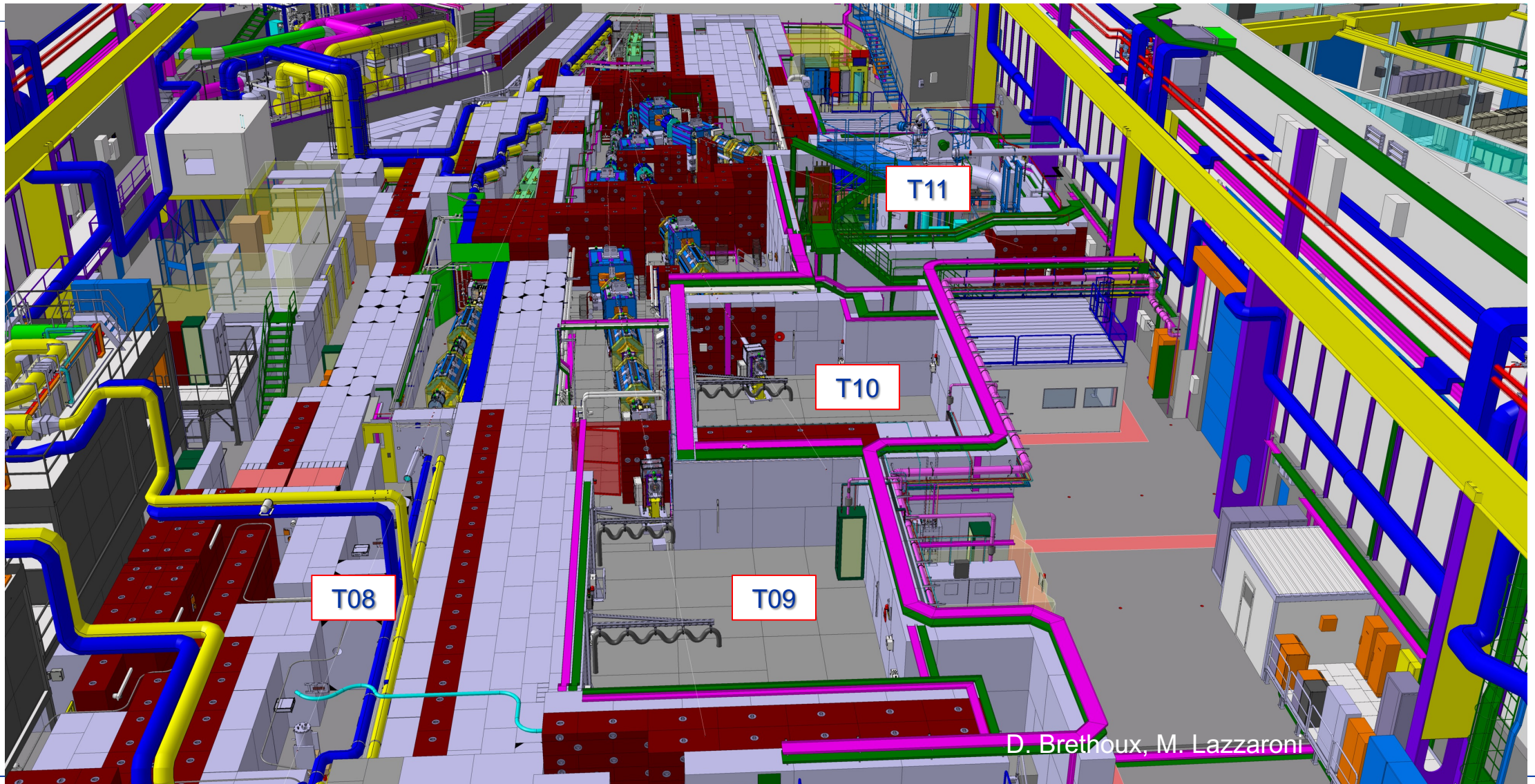
East Area Renovation



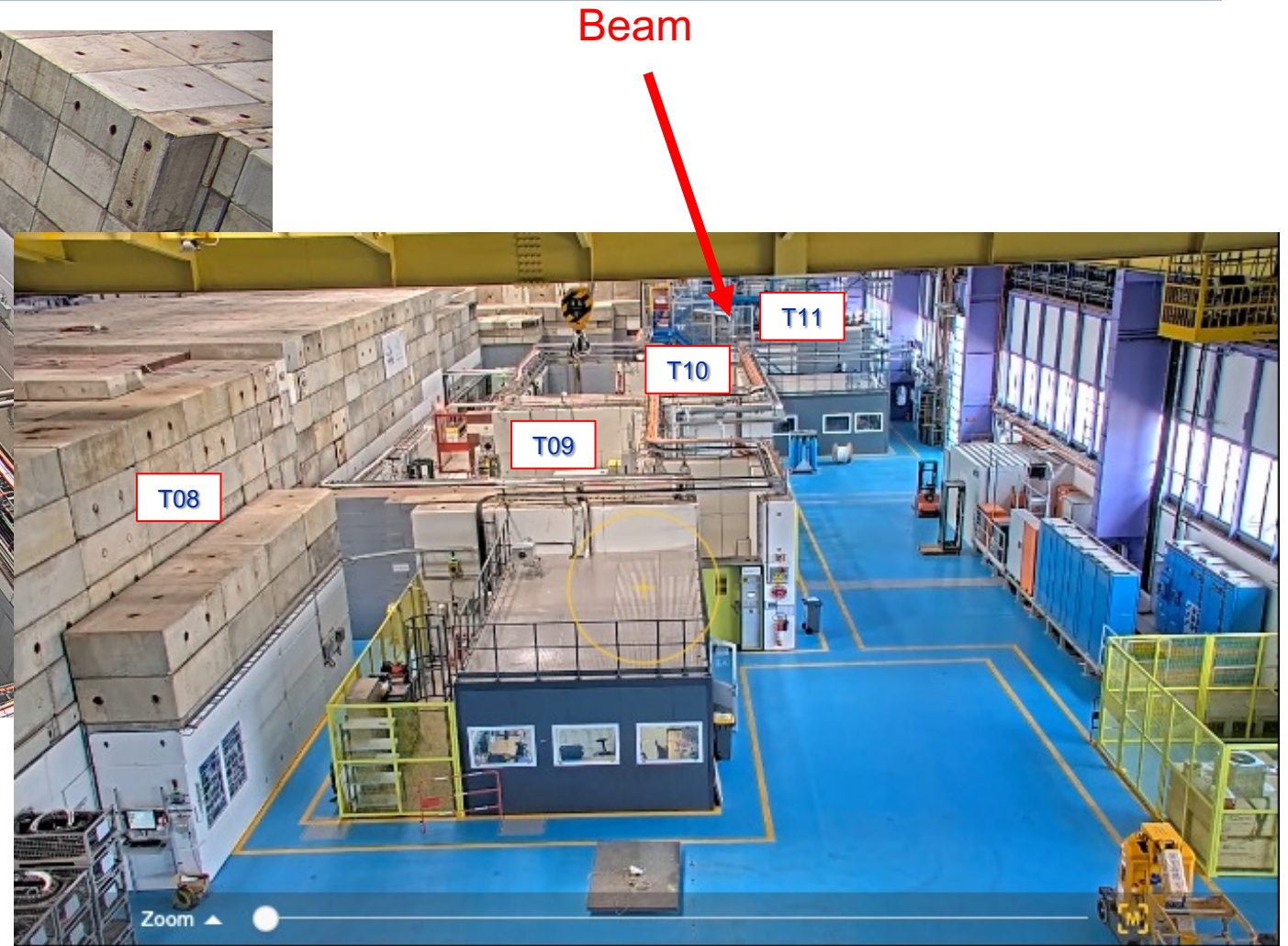
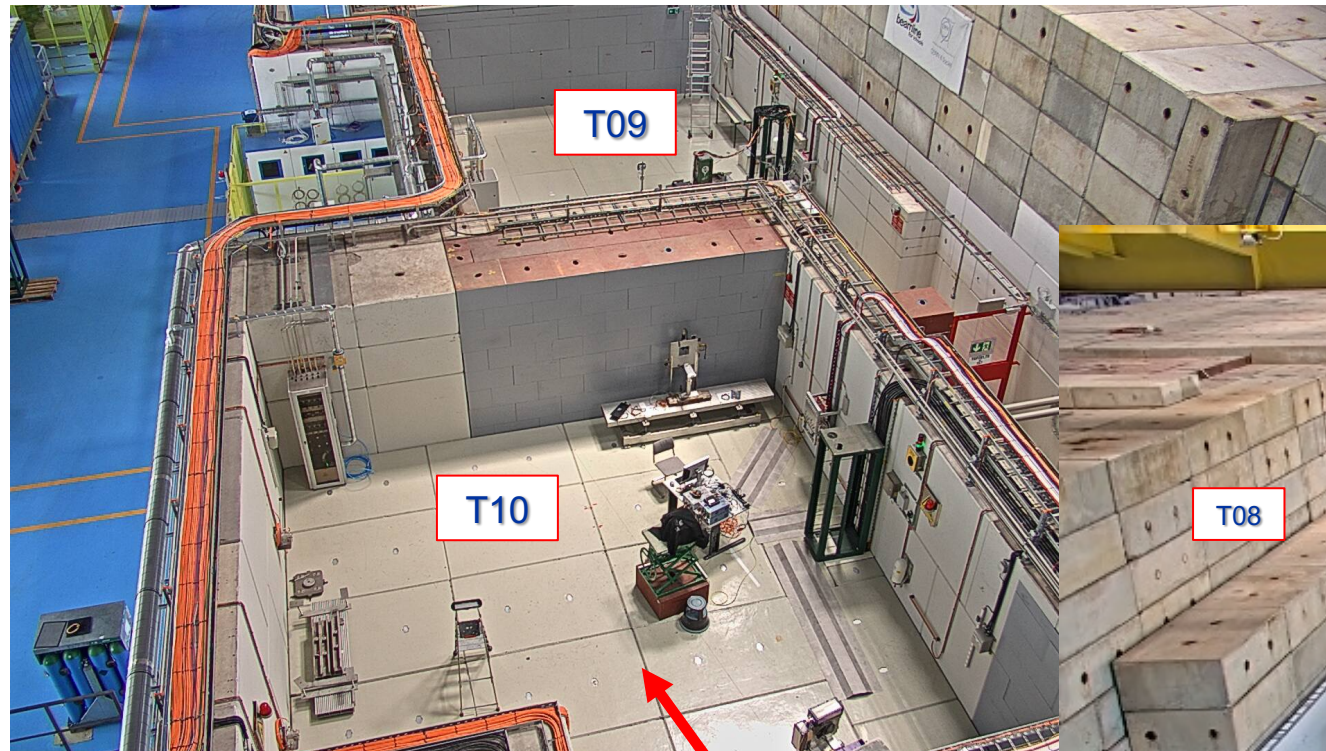
- The East Area Renovation was completed during the LS2.
- The renovation included
 - Full refurbishment of the East Hall with its beamlines and infrastructures
 - Upgrade of B157, its heating/ventilation, improved thermal insulation, wall and roof cladding (asbestos), separated cooling for primary and secondary beamlines.
 - Improved radiation protection.
 - Improved equipment accessibility and faster repair times, primary beam dump just downstream of the primary target.
 - Change in the beamline layout
 - Higher max. p and improved selectivity of particle types.
 - Completely new magnet powering scheme
 - Cycled powering leading to reduction of annual power consumption from 11 to 0.6 GWh, less magnet types for better maintenance.



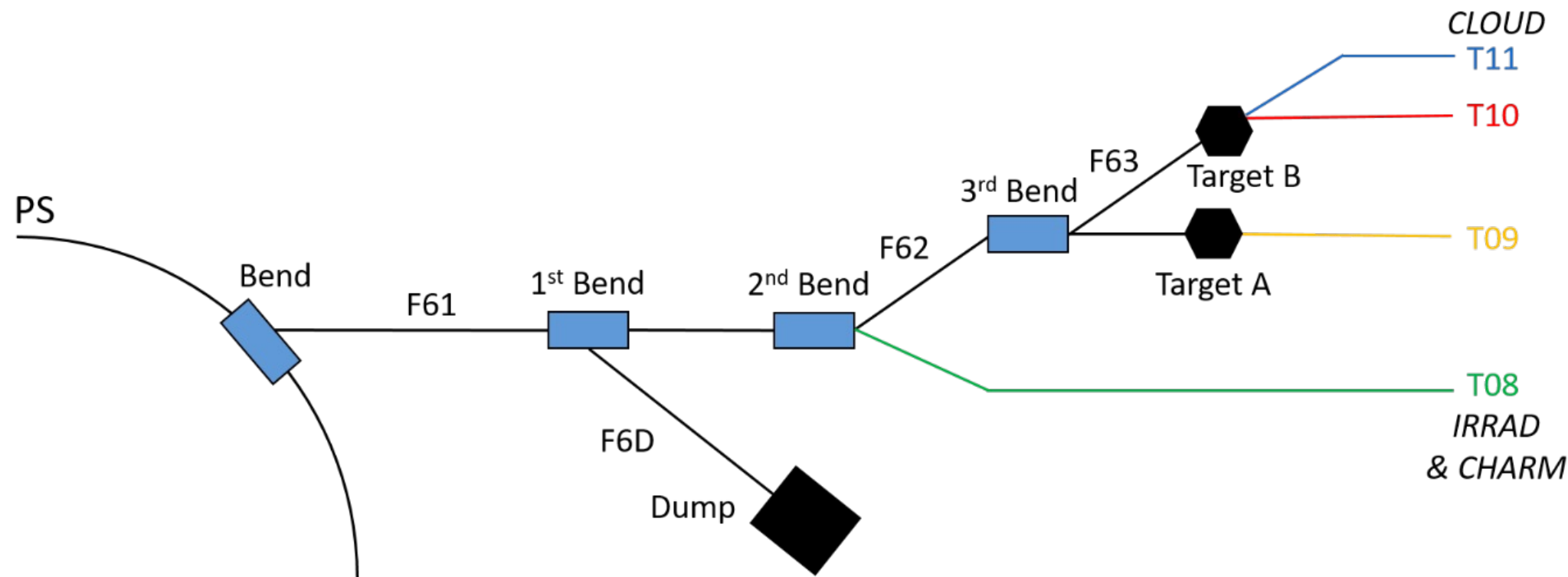
Current Layout



Current Layout

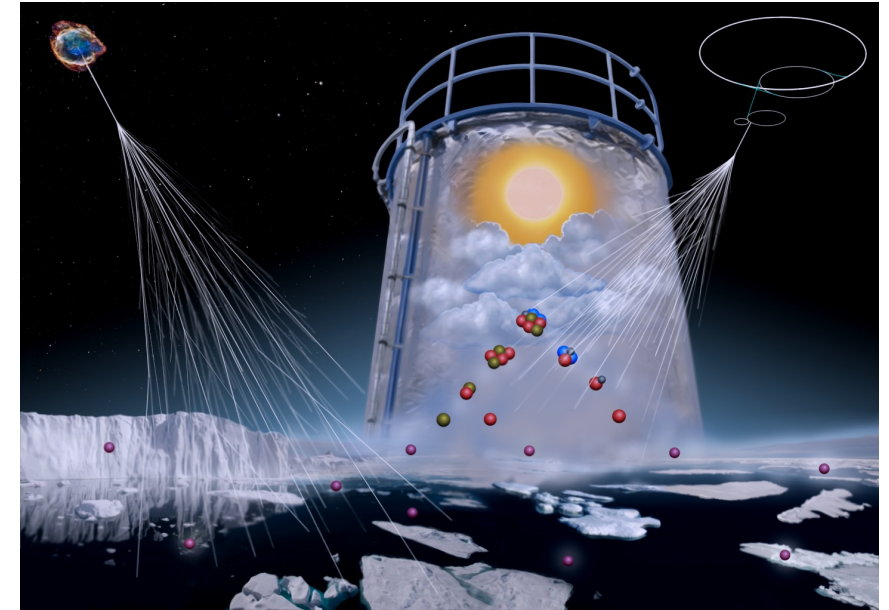


East Area Beams



Experiments: CLOUD

- Studies the influence of cosmic rays to cloud formation
- Cloud expansion chamber set-up with extensive instrumentation (mass spectrometers, particle counters, etc.)
- Uses PS beam as first and only particle beam experiment to study atmospheric and climate science
- Spectacular results achieved (several publications in Nature and Science)

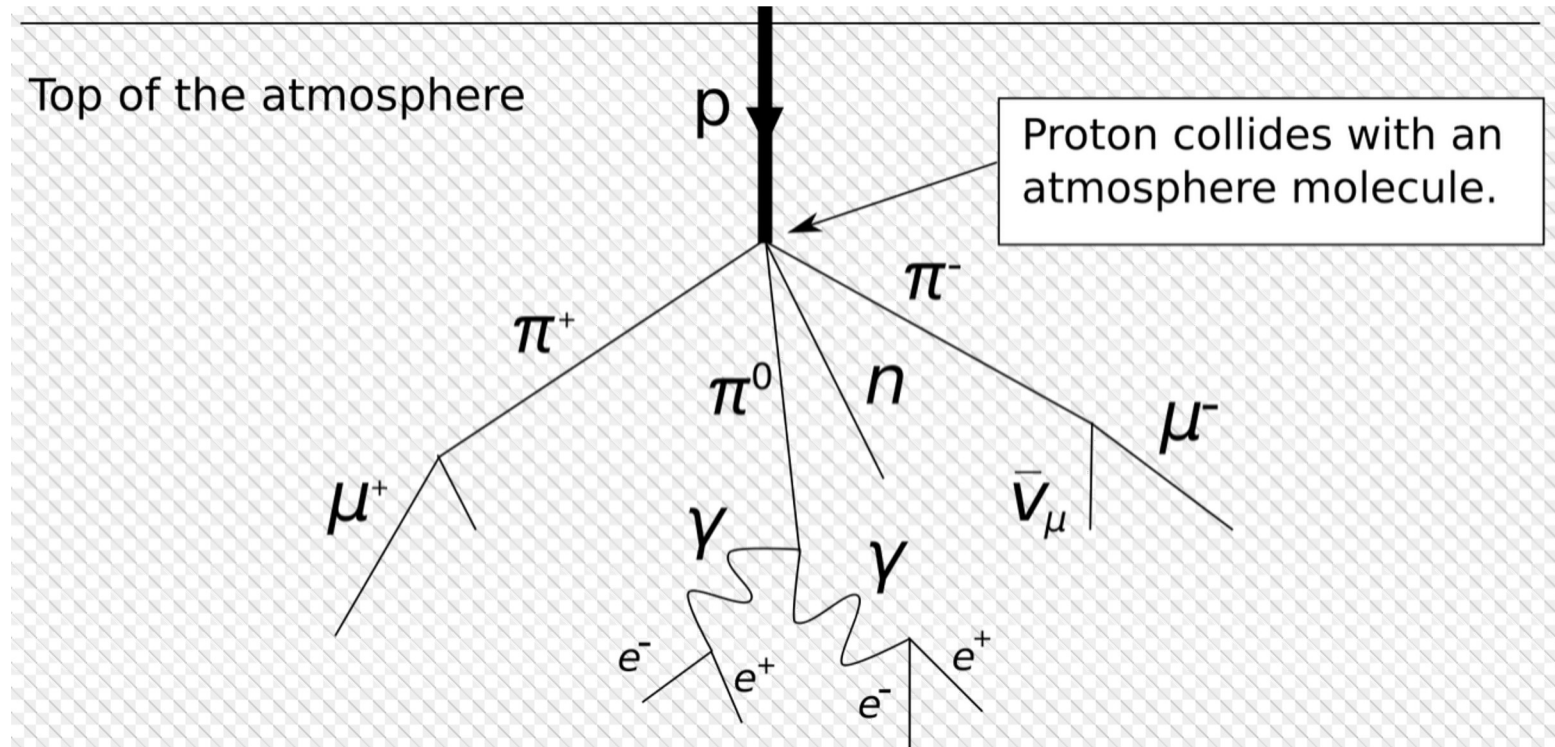


How do we produce a secondary beam ?

Targets and particle production

Principle taken from cosmic radiation

- Primary proton beam initiating hadronic shower
- Always followed by an electro-magnetic shower
- Particles are produced at once in a large momentum range



Targets and particle production

		Name		Q	Mass	Mean life (τ)		CT	Mean decay distance	Decays
					[MeV/c ²]	[s]		[m]	[m/GeV/c]	
Leptons	Electron	e	±e	0.511	stable					
	Muon	μ	±e	105.6	2.2×10 ⁻⁶		659.6	6.3×10 ³	μ ⁺ → e ⁺ ν̄ _e ν _μ (100%)	
Hadrons	Pion	π	±e	139.6	2.6×10 ⁻⁸		7.8	56.4	π ⁺ → μ ⁺ ν _μ (100%)	
	Kaon	K	±e	493.6	1.23×10 ⁻⁸		3.7	8.38	K ⁺ → μ ⁺ ν _μ (63%) π ⁰ e ⁺ ν _e (5%) π ⁰ μ ⁺ ν _μ (3%) π ⁺ π ⁰ (...) (28.9%)	
		K ⁰	0	497.6	K ⁰ _S	8.9×10 ⁻¹¹	0.02	0.060	K ⁰ _S → π ⁰ π ⁰ (30.7%) π ⁺ π ⁻ (69.2%)	
					K ⁰ _L	5.12×10 ⁻⁸	15.34	34.4	K ⁰ _L → π [±] e [∓] ν _e (40.5%) π [±] μ [∓] ν _μ (27.0%) 3 π ⁰ (19.5%) π ⁺ π ⁻ π ⁰ (12.5%)	
	Proton	p	±e	938	stable					
	Lambda	Λ	0	1115.6	2.63×10 ⁻¹⁰		0.079	0.237*	Λ ⁰ → p π ⁻ (63.9%)	
	Baryons	Sigma	Σ ⁺	+e	1189.3	8.02×10 ⁻¹¹		0.024	0.068*	Σ ⁺ → p π ⁰ (51.57%)
Hyperons		Σ ⁻	-e	1197.4	1.48×10 ⁻¹⁰		0.044	0.125*	Σ ⁻ → n π ⁻ (99.84%)	

(*) for 10 GeV/c

Targets and particle production

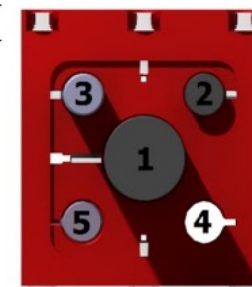
HADRON TARGET



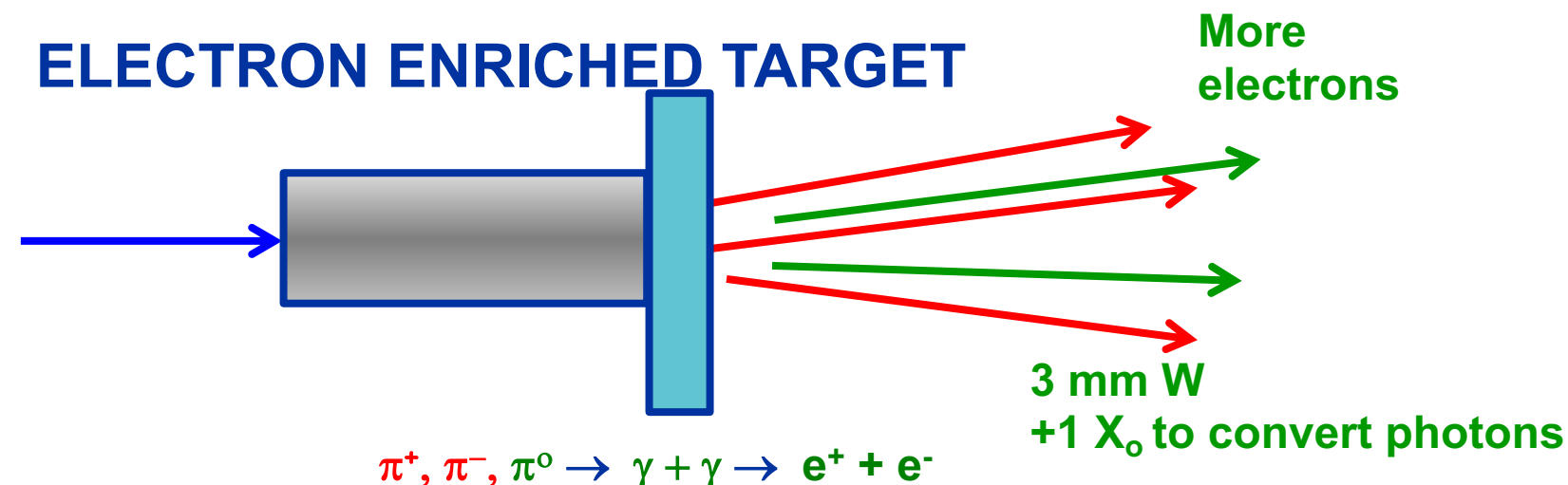
100-200 mm AL or BE, i.e. Low-Z material
Up to $1 \lambda_{\text{int}}$ and $0.5 X_0$

T9/T10/T11 Multitarget Configuration

Head	Material	Length (mm)	Diameter (mm)	Comments
1	Be	200	10 + Al case	Electron enriched
2	W	3	10	Electron enriched
3	Al	100	10	
4	W	3	10	Hadron
5	Al	200	10	Empty
	Air	-	-	Hadron
	Al	20	10	Hadron



ELECTRON ENRICHED TARGET



How do we build a beamline?

Beam lines

Experiments and test beams require “clean” beams with high purity (one particle type) and small momentum spread

Beam lines design (“optics”)

1. Collect produced particles from target
2. Select momentum
3. Select particle type
4. Transport beam to experiment
5. Select beam spot size for experiment

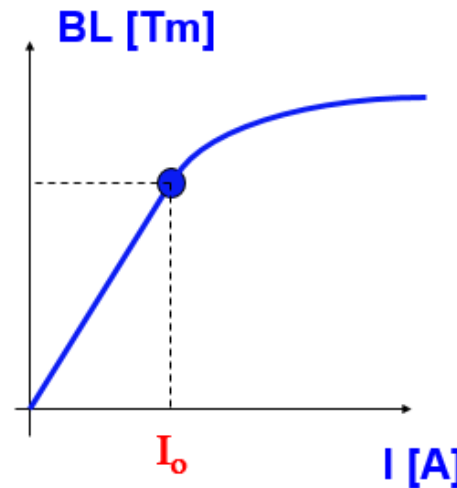
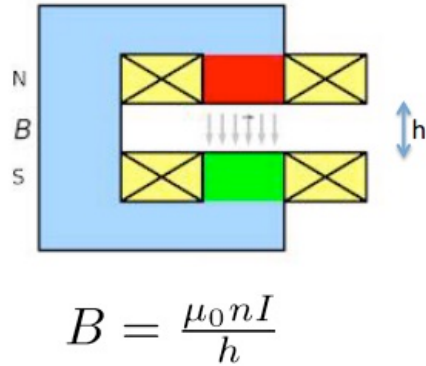
Secondary beam line - layout

Basic beam design

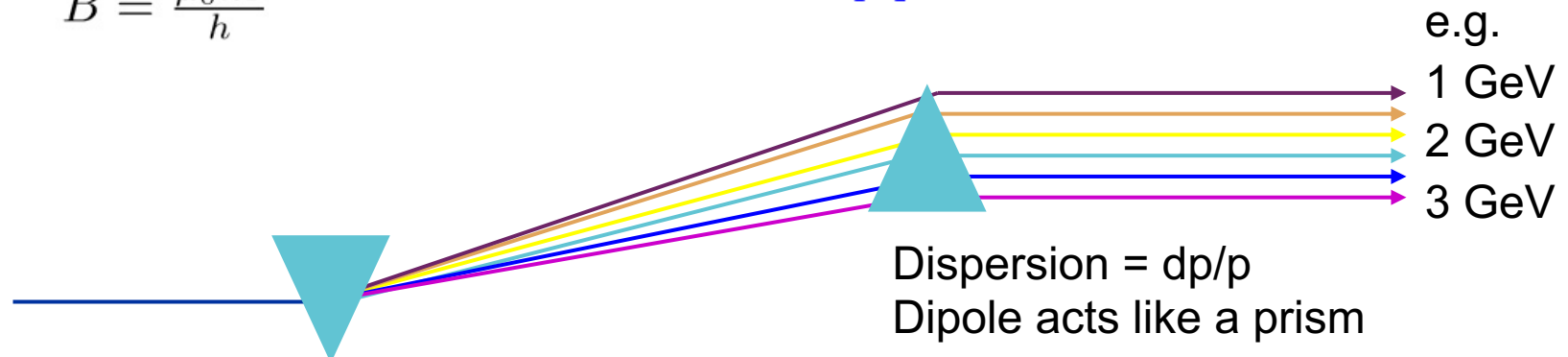
Transport and momentum selection: bending magnets

Dipole electro-magnets:

$$\vec{F} = q \cdot \vec{v} \times \vec{B}$$



$$\theta \text{ [mrad]} = \frac{299.79 BL \text{ [T} \cdot \text{m]}}{p \text{ [GeV]}}$$



Secondary beam line - layout

Basic beam design

Transport and focus: Quadrupole Magnets

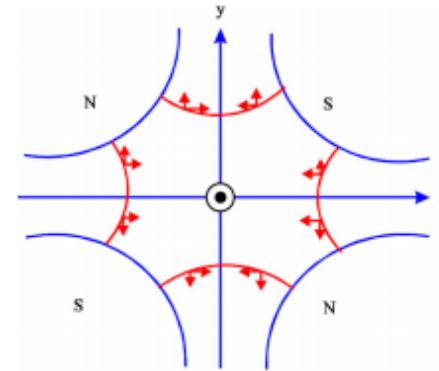
E.g. in the horizontal plane

$$F(x) = q \cdot v \cdot B(x)$$

We want a magnetic field that

$$B_y = g \cdot x \quad B_x = g \cdot y$$

→ Quadrupole magnet



The red arrows show the direction of the force on the particle

Gradient of quadrupole

$$g = \frac{2\mu_0 n I}{r^2} \left[\frac{T}{m} \right]$$

Normalized gradient, focusing strength

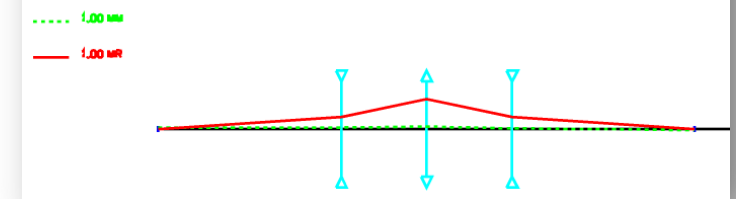
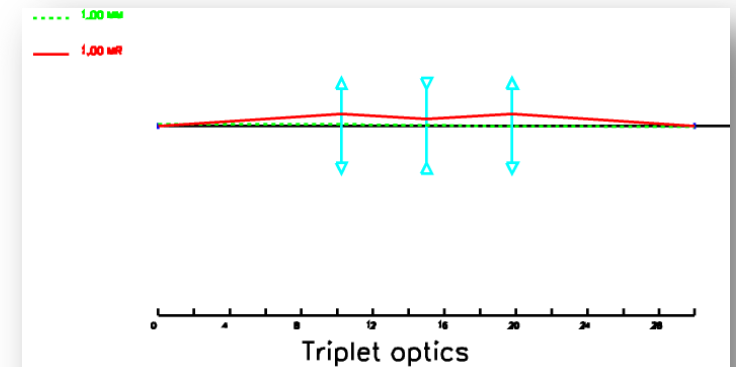
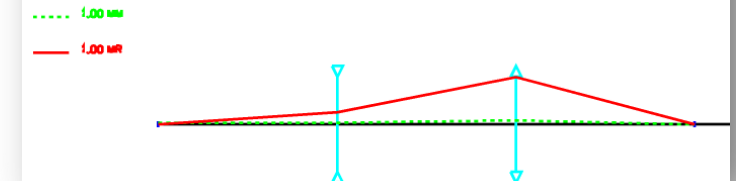
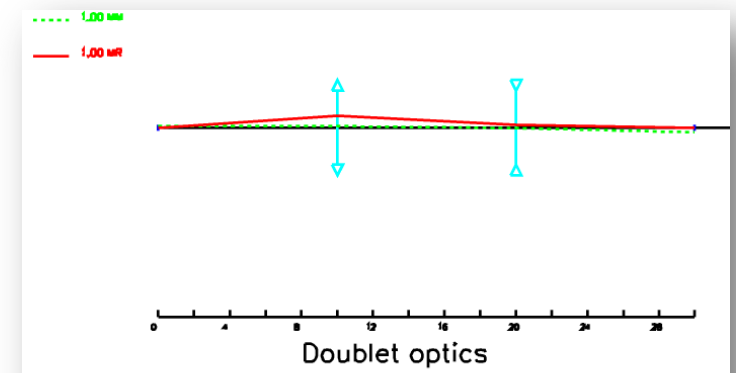
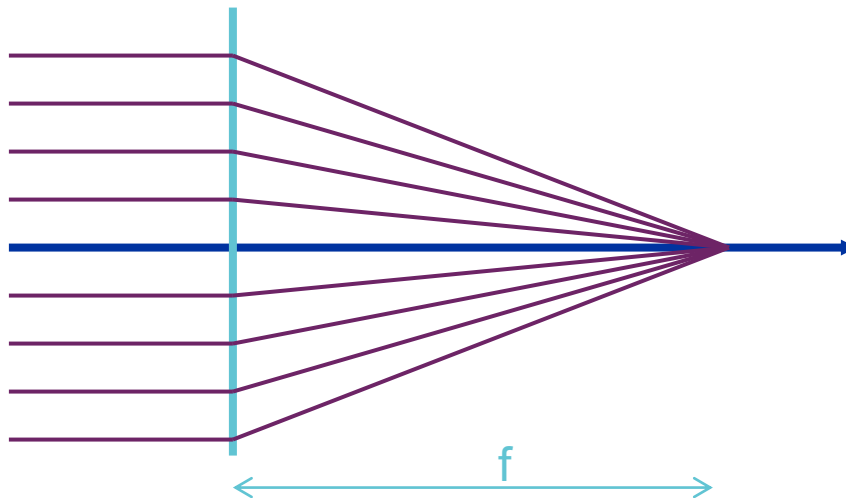
$$k = \frac{g}{p/e} [m^{-2}]$$

Secondary beam line - layout

Basic beam design

Transport and focus: Quadrupoles

- Like an optical lens
- Difference: focusing in one plane and defocusing in the other plane at the same time
- Use doublets or triplets for transport and focus

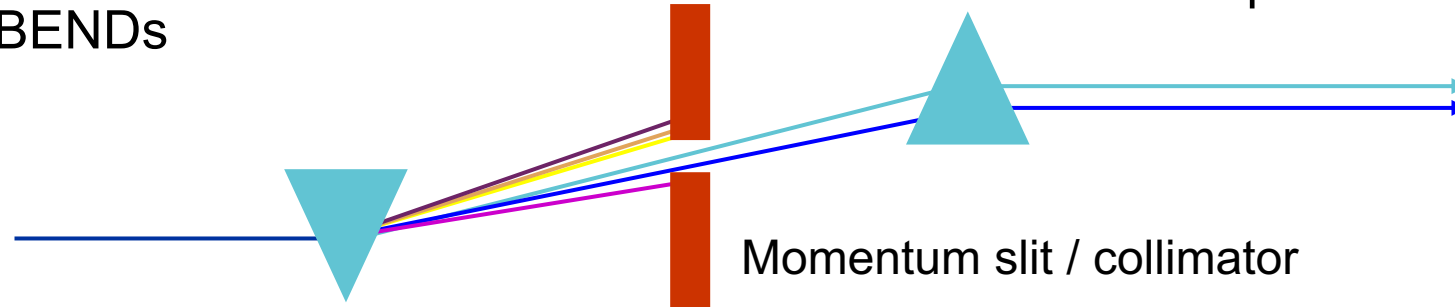


Secondary beam line - layout

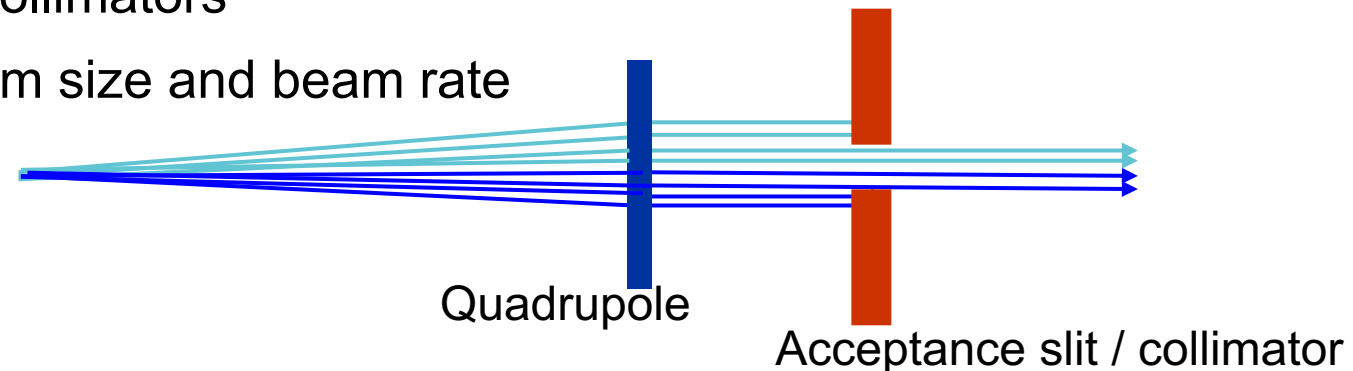
Basic beam design

Momentum selection and acceptance: collimators

- Select small momentum band in combination with dispersion from BENDs

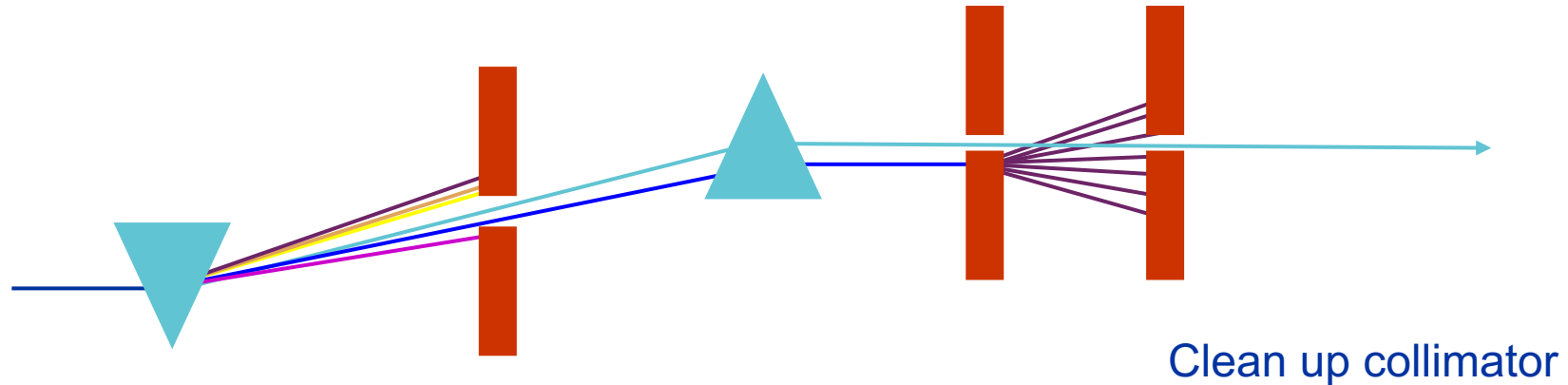


- Acceptance collimators
 - Select beam size and beam rate



Secondary beam line - layout

- **Clean up collimators**
 - Absorb secondary particles produced in acceptance collimators



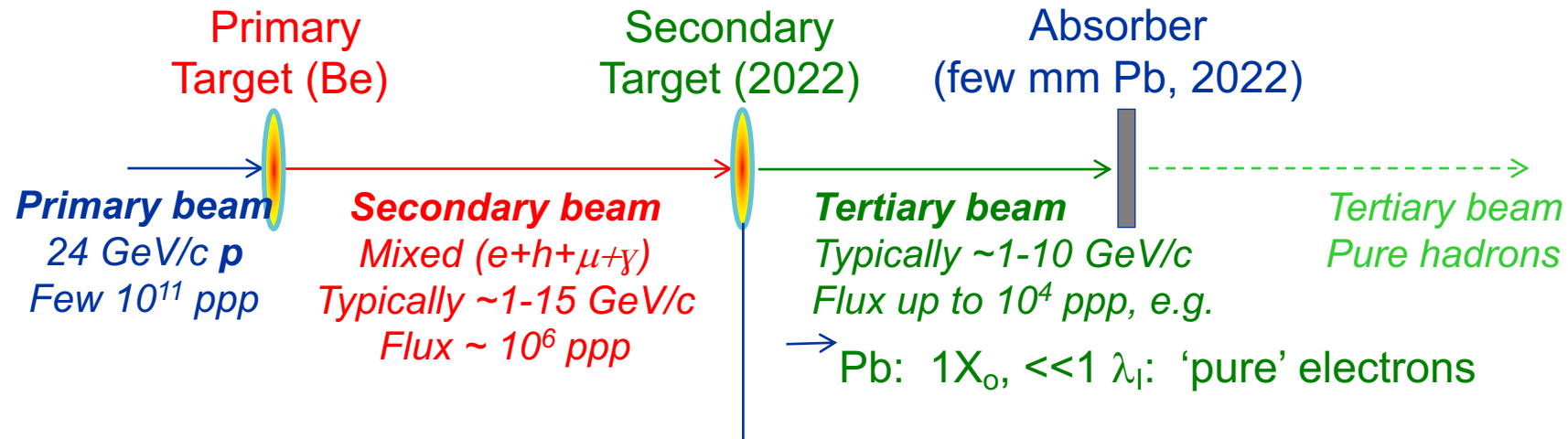
- **TAX (Target attenuator, only North Area)**
 - Define initial acceptance of the beam line



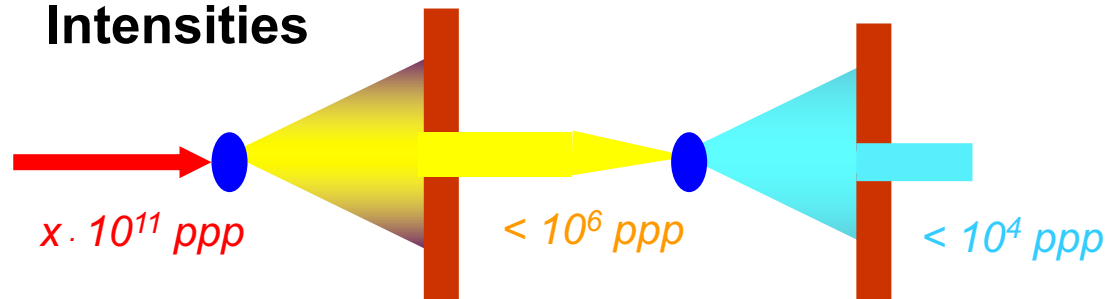
Secondary beam line - layout

Basic beam design

Selection of particle types



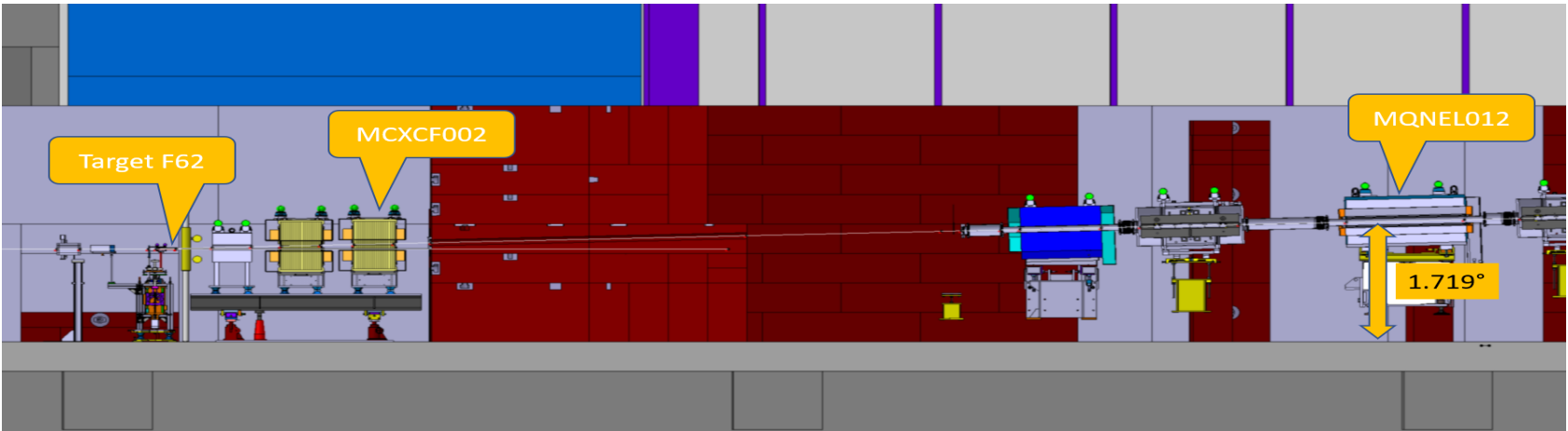
Intensities



Characteristics of the East Beams

Parameter	T09 Target		T10/T11 Target	
Beam Line	T09		T10	T11
Secondary beam Max Momentum (GeV/c)	16		12	3.5
$\Delta p/p$ (%)	± 0.7 to ± 15.0		± 0.7 to ± 15.0	± 0.7 to ± 15.0
Maximum intensity/spill (hadrons/electrons)	10^6		10^6	10^6
Available particle types	Pure electrons (T09) or mixed/pure hadrons or pure muons			

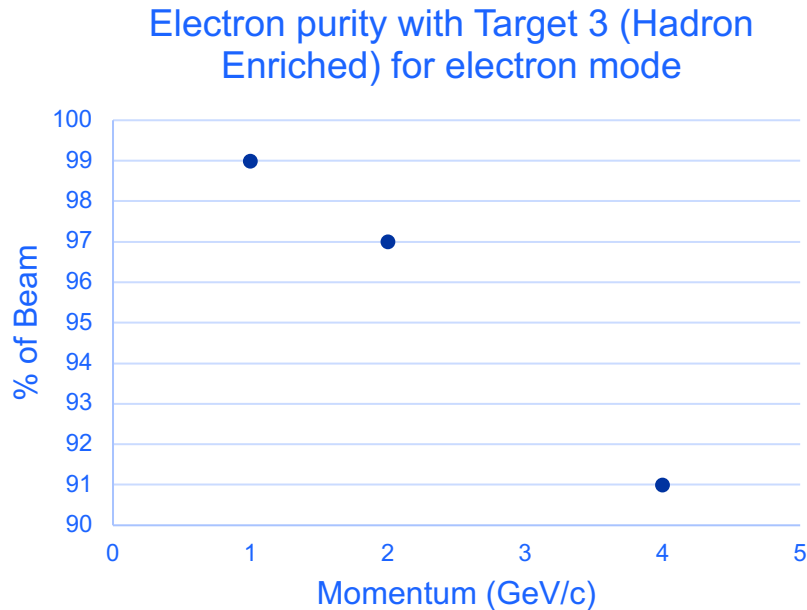
30-35 mrad vertical production angle



T9 Beam Modes available

- **Electron mode**

- The charged particles from the secondary target are deflected away selecting the photons. A 5 mm Pb converts the photons into e^+/e^- pair.
- Momenta 0.1 GeV/c – 4 GeV/c.
- > 99% purity for $p < 1$ GeV/c

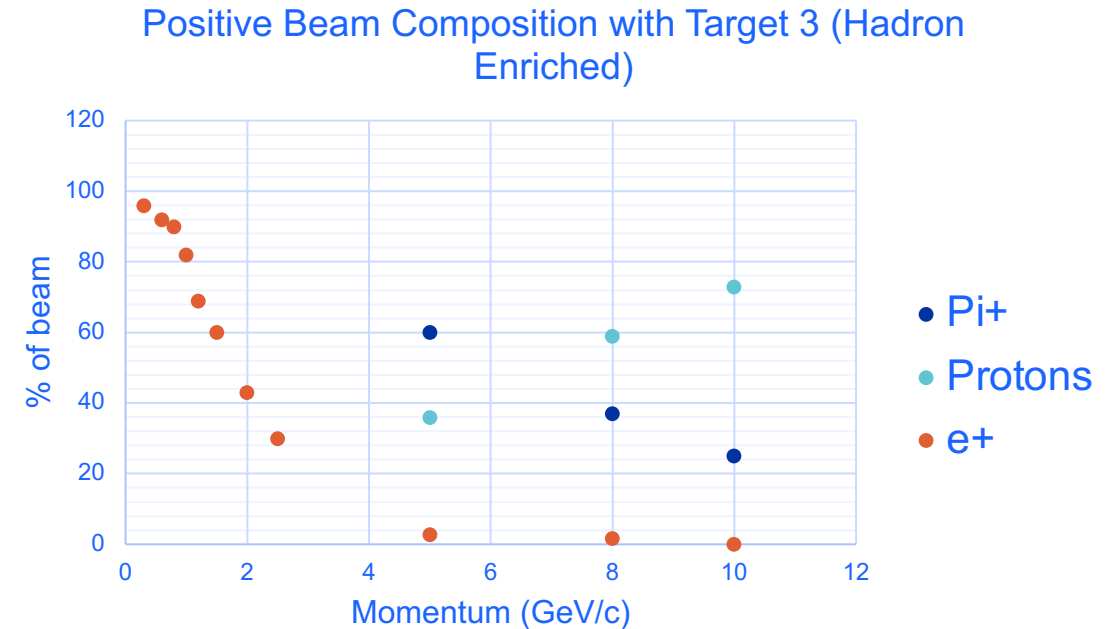


Only XCET available for beam composition data

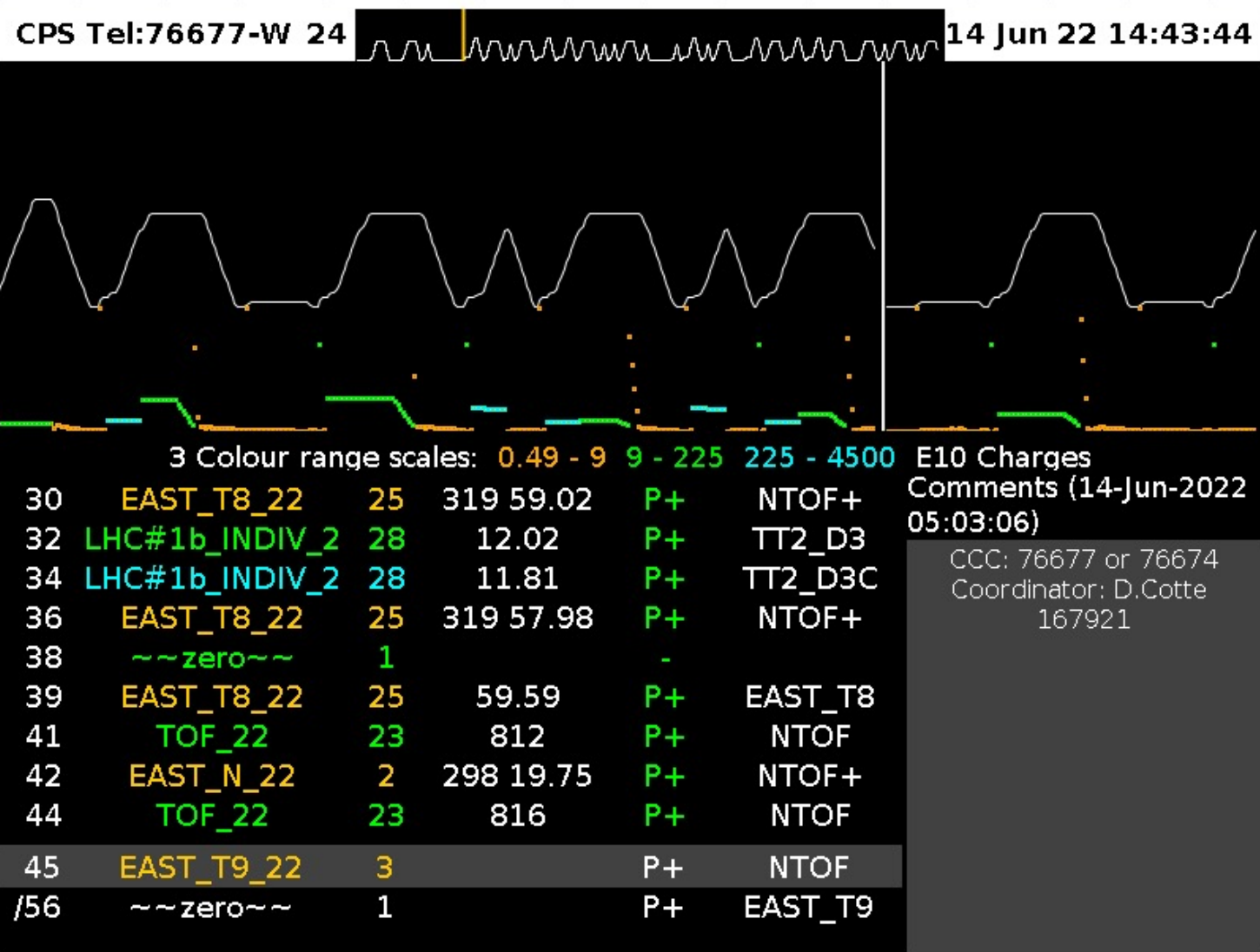
• e^-

- **Mixed hadron mode**

- The secondary beam from protons on target can be chosen.
 - Momenta 0.1 GeV/c – 16 GeV/c.
 - At lower momenta electrons dominate.



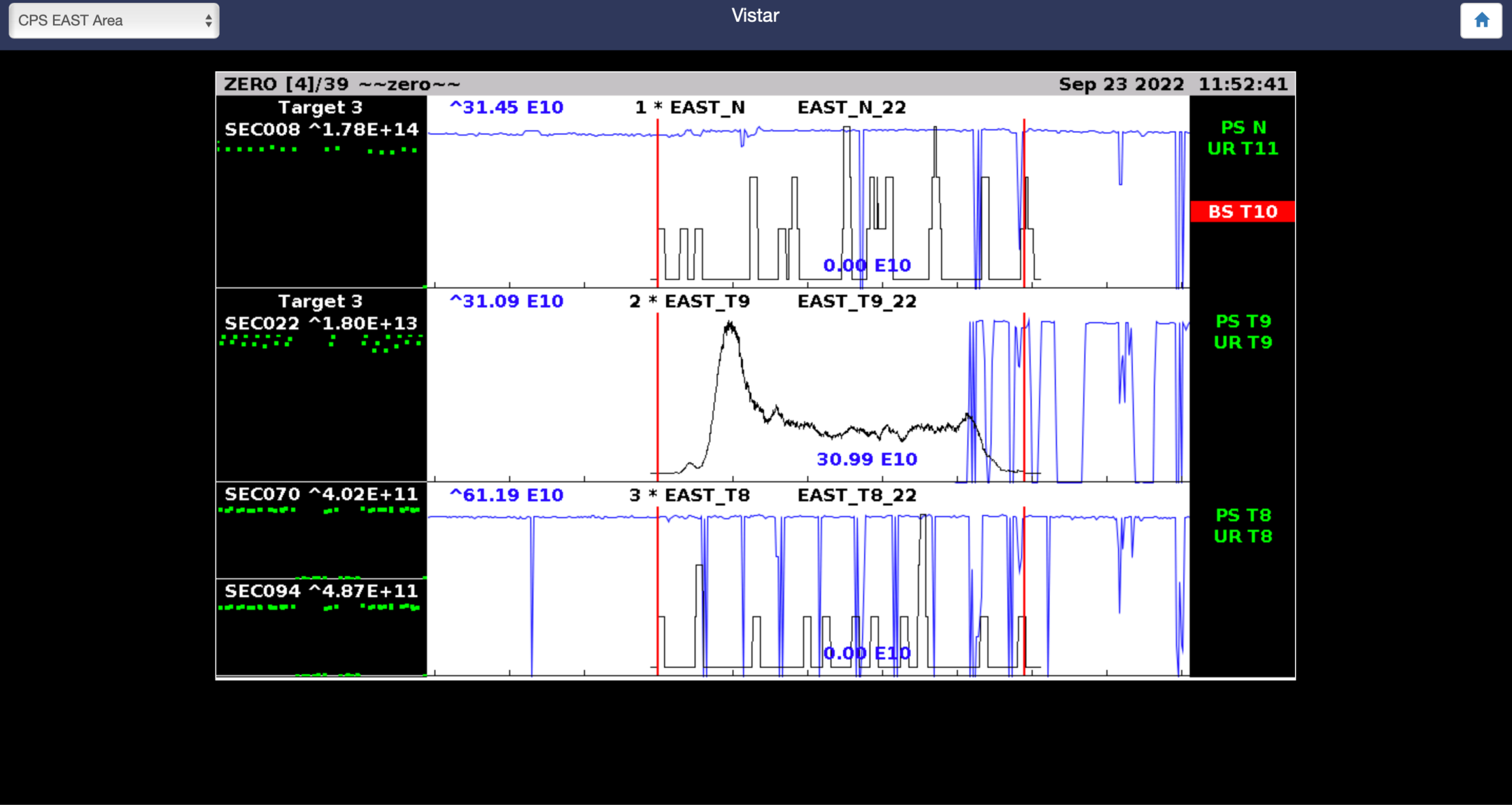
Spill Structure



Spill duration: 0.4 second flat top
Usually : 1-2 cycles per minute per **East Destination**
Max 6 East cycles / 40 seconds → RP Limit

Super-cycle structure dependent on all users (SPS, nTOF ...)

Spill Structure

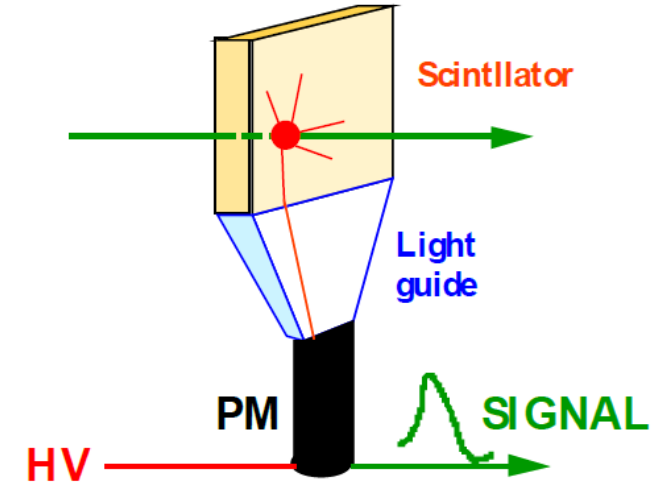


How do we see the beam?

Secondary beam line - Instrumentation

Scintillating Counter (XSCI)

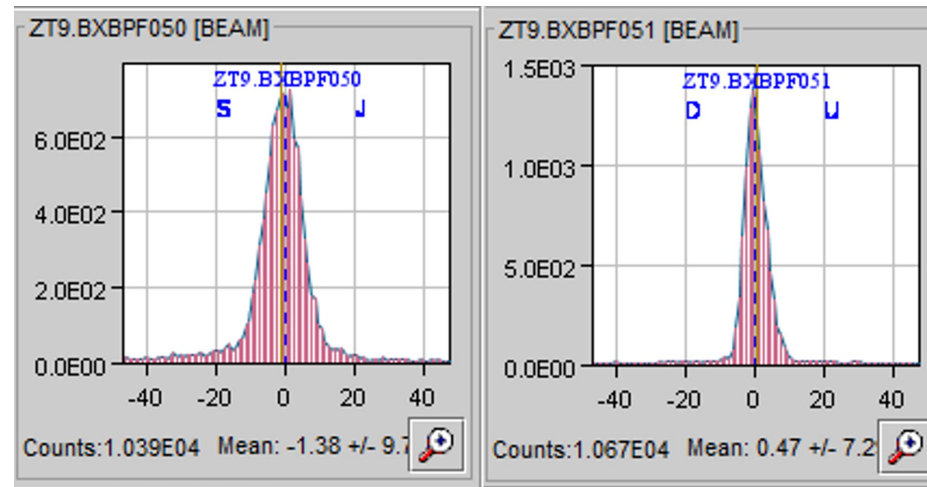
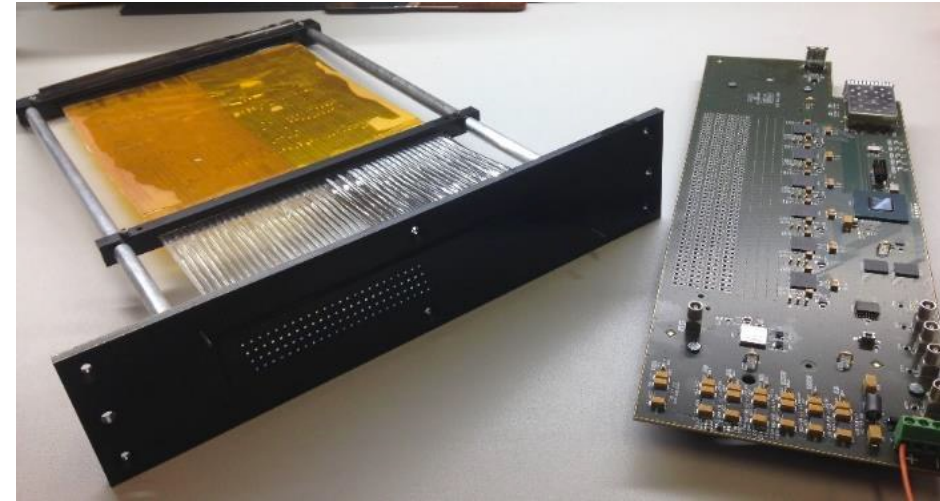
- Charged particles produce light in scintillator
- Light collected and transported by light guide
- Coupled to photo multiplier tube (PM), light hits photocathode and produces electrons
- Electrons are amplified within a high voltage cascade
- Used to count particles in a range from a few particles up to rates of MHz
- Different shapes and sizes: Some can scan through a beam, other count the total rate



Secondary beam line - Instrumentation

Scintillating fibre hodoscopes (XBPF)

- Particle detection with scintillating fibres from the creation of scintillation light, due to the passage of a charged particle, and the transmission of this light inside the fibre by total internal reflection.
- Composed of 100 or 200 scintillating fibres of 1 mm thickness and square cross-section



Secondary beam line - Instrumentation

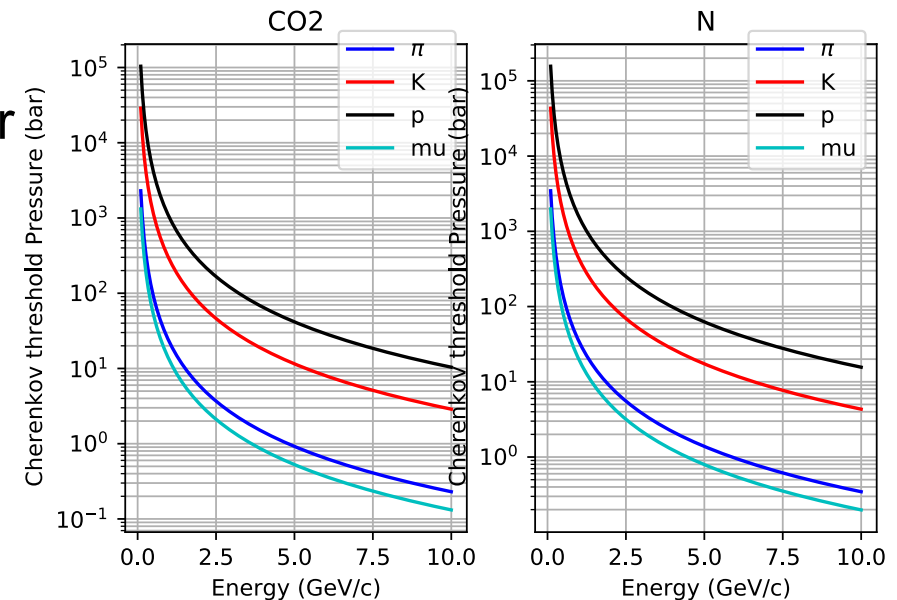
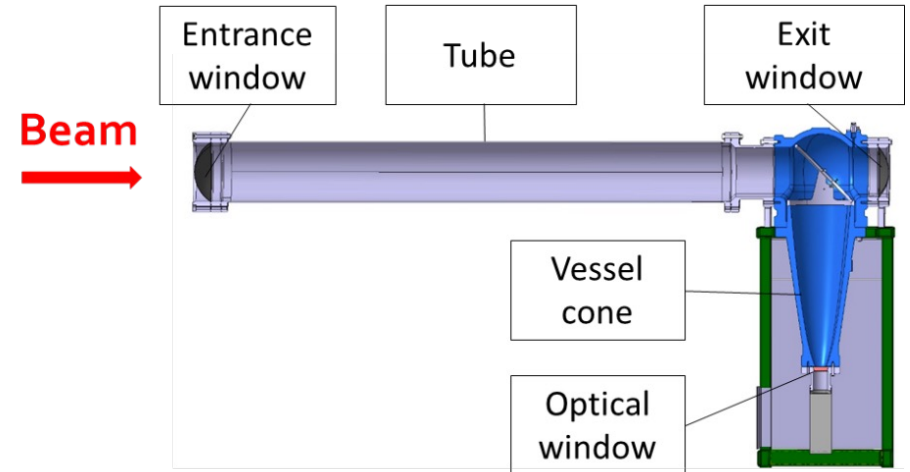
Threshold Cerenkov counters (XCET)

- In a medium (e.g., He or CO₂ gas) if a charged particle goes faster than light it emits Cerenkov light in a cone with half-opening angle f :

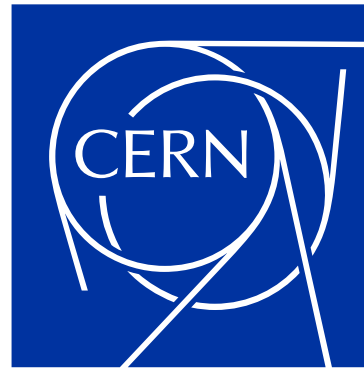
$$f^2 = 2kP - m^2 / p^2$$

where k depends on the gas, P =pressure.

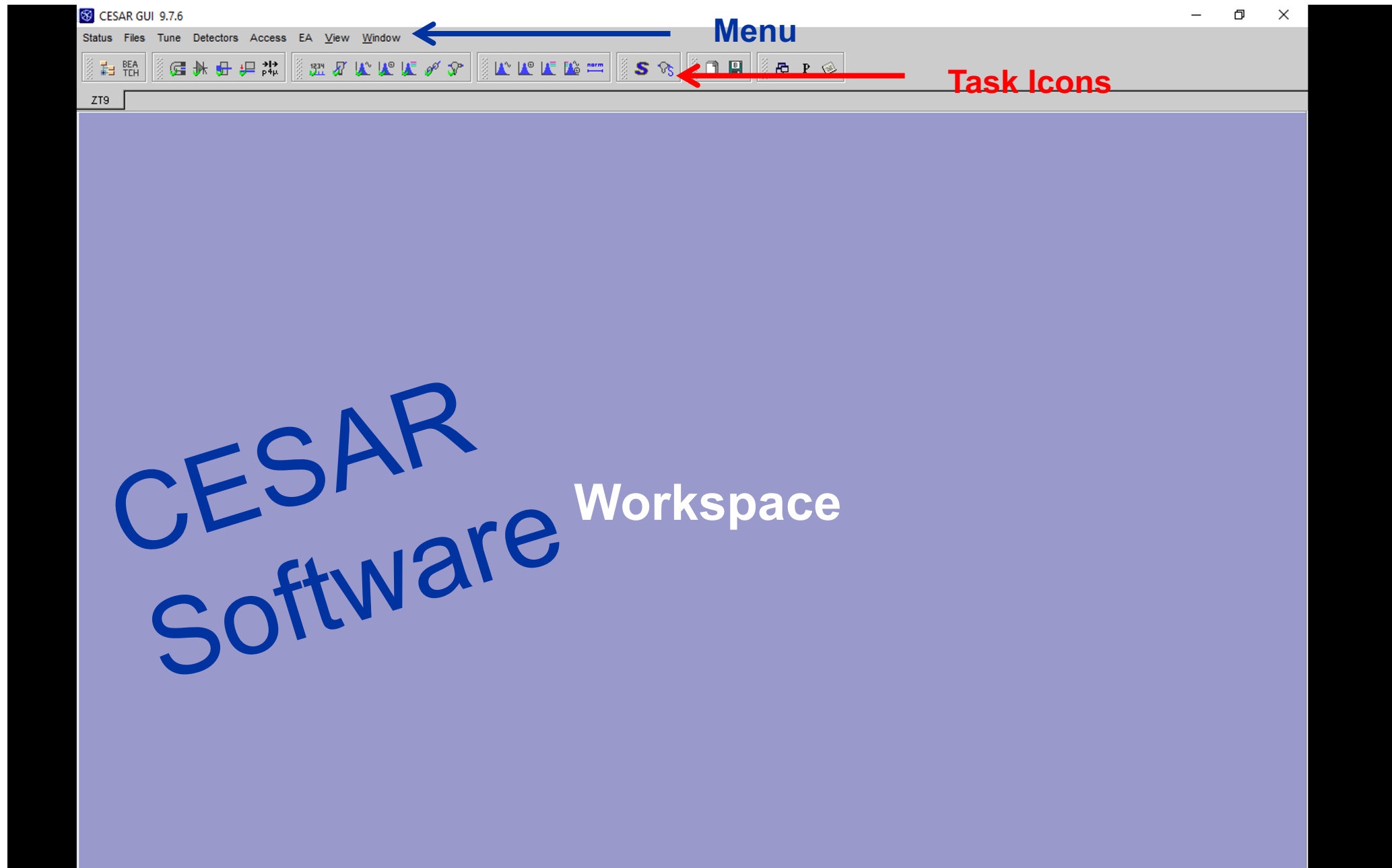
- By selecting the right operating pressure, one type of particle has good efficiency and the other gives no signal. By making a coincidence with scintillator signals, particle identification can be made.
- Two types of XCET in T09:
 - Low pressure \rightarrow 0.01 – 4 bars
 - High pressure \rightarrow 0.01 – 15 bars



**Congratulations for having won this competition
and good luck for a successful experiment!
Have a wonderful time at CERN !**



How do we control the beam?



CESAR GUI 9.7.6

Status Files Tune Detectors Access EA View Window

BEA TCH

ZT9

Magnet Status [Magnets]

Beam: ZT9 / ZT9-EXP
File: ZT9A.ZT9-EXP.567
Momentum: +15.00 GeV/c
Comment: BL4S 15 GeV positive hadrons focus 10 m from XBPF 51

Magnets	Read	BeamRef	Max	Duration	Polarity	Info	F	Comments
△ ZT9.DHZ01	0.0	0.0	220	0.449999988079	N			
△ ZT9.DHZ02	0.0	0.0	220	0.400000005960	N			
◇ ZT9.QFN01	302.0	302.0	349	0.400000005960	N			
◇ ZT9.QDN02	399.6	399.6	450	0.400000005960	S			
◇ ZT9.QFN03	302.0	302.0	349	0.400000005960	N			
△ ZT9.BHZ01	852.0	852.0	1009	0.400000005960	N			
◇ ZT9.QFN04	340.0	340.0	396	0.400000005960	N			
◇ ZT9.QFN05	340.0	340.0	396	0.400000005960	N			
△ ZT9.BHZ02	852.0	852.0	1009	0.400000005960	N			
◇ ZT9.QDN06	666.0	666.0	833	0.400000005960	S			
△ ZT9.BVT01	635.0	635.0	949	0.400000005960	S			
◇ ZT9.QFN07	362.0	362.0	654	0.400000005960	N			
◇ ZT9.QDN08	140.9	140.9	541	0.400000005960	S			
△ ZT9.DHZ03	-0.0	0.0	220	0.400000005960	N			DEST_ECO

☒ Run
☐ Hold

☒ Refresh
☐ Refresh All
☐ Refresh Selected

Magnets x

M. Van Dijk on behalf of BE-EA-LE

CESAR GUI 9.7.6

Status Files Tune Detectors Access EA View Window

BEA TCH

ZT9

Magnet Status [Magnets]

Beam: ZT9 / ZT9-EXP
File: ZT9A.ZT9-EXP.567
Momentum: +15.00 GeV/c
Comment: BL4S 15 GeV positive hadrons focus 10 m from XBPF 51

Magnets	Read	BeamRef	Max	Duration	Polarity	Info	F	Comments
△ ZT9.DHZ01	0.0	0.0	220	0.449999988075	N			
△ ZT9.DHZ02	0.0	0.0	220	0.400000005960	N			
◇ ZT9.QFN01	302.0	302.0	349	0.400000005960	N			
◇ ZT9.QDN02	399.6	399.6	450	0.400000005960	S			
◇ ZT9.QFN03	302.0	302.0	349	0.400000005960	N			
△ ZT9.BHZ01	852.0	852.0	1009	0.400000005960	N			
◇ ZT9.QFN04	340.0	340.0	396	0.400000005960	N			
◇ ZT9.QFN05	340.0	340.0	396	0.400000005960	N			
△ ZT9.BHZ02	852.0	852.0	1009	0.400000005960	N			
◇ ZT9.QDN06	666.0	666.0	833	0.400000005960	S			
△ ZT9.BVT01	635.0	635.0	949	0.400000005960	S			
◇ ZT9.QFN07	362.0	362.0	654	0.400000005960	N			
◇ ZT9.QDN08	140.9	140.9	541	0.400000005960	S			
△ ZT9.DHZ03	-0.0	0.0	220	0.400000005960	N			

Run Hold Refresh Refresh All Refresh Selected Set Current Set Duration Results Rectifier Status Store to e-logb...

Set ZT9.QFN07 Current

Current 362.0 [Amp]

☒ update Beam Reference

OK Cancel

CESAR GUI 9.7.6

Status Files Tune Detectors Access EA View Window

BEA TCH

Rectifier Status [Rectifiers]

Beam: ZT9 / ZT9-EXP
File: ZT9A.ZT9-EXP.567
Momentum: +15.00 GeV/c
Comment: BL4S 15 GeV positive hadrons focus 10 m from XBPF 51

Rectifiers	CURRENT	BeamRef	TOL	MODE	POL	LOC	FAULT	Info	Comments
▲ ZT9.DHZ01	0.0	0.0	0.4	ON	N			null / T9.DHZ01	
▲ ZT9.DHZ02	0.0	0.0	0.4	ON	N			null / T9.DHZ02	
▲ ZT9.QFN01	302.0	302.0	0.4	ON	N			null / T9.QFN01	
▲ ZT9.QDN02	399.6	399.6	0.4	ON	N			null / T9.QDN02	
▲ ZT9.QFN03	302.0	302.0	0.4	ON	N			null / T9.QFN03	
▲ ZT9.BHZ01	852.0	852.0	0.4	ON	N			null / T9.BHZ01	
▲ ZT9.QFN04	340.0	340.0	0.4	ON	N			null / T9.QFN04	
▲ ZT9.QFN05	340.0	340.0	0.4	ON	N			null / T9.QFN05	
▲ ZT9.BHZ02	852.0	852.0	0.4	ON	N			null / T9.BHZ02	
▲ ZT9.QDN06	666.0	666.0	0.4	ON	N			null / T9.QDN06	
▲ ZT9.BVT01	635.0	635.0	0.4	ON	N			null / T9.BVT01	
▲ ZT9.QFN07	362.0	362.0	0.4	ON	N			null / T9.QFN07	
▲ ZT9.QDN08	140.9	140.9	0.4	ON	N			null / T9.QDN08	
▲ ZT9.DHZ03	-0.0	0.0	0.4	ON	I			null / T9.DHZ03	

Run Hold Refresh Refresh All Refresh Selected Set Curr. ON STANDBY OFF RESET Display ... Store to ...

Rectifiers x

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Status Files Tune Detectors Access EA View Window

BEA TCH

1234

norm


S

P

ZT9

Beam stopper Status [Beam stopper]

Beam: ZT9 / ZT9-EXP
File: ZT9A.ZT9-EXP.567 Momentum: +15.00 GeV/c Comment: BL4S 15 GeV positive hadrons focus 10 m from XBPF 51

Beam stopper	Read	BeamRef	Info	Comments
 ZT9.TBS017	IN	OUT		<>BeamRef

☒ Run ☐ Hold ☒ Refresh ☐ Refresh All ☐ Refresh Selected

Beam stopper x

CESAR GUI 9.7.6

Status Files Tune Detectors Access FA View Window

BEA TCH

ZT9

1234 Scaler Status [Scalers]

Beam: ZT9 / ZT9-EXP
File: ZT9A.ZT9-EXP.567 Momentum: +15.00 GeV/c Comment: BL4S 15 GeV positive hadrons focus 10 m from XBPF 51

Scalers	Count	Normalized C...	Norm count (...)	Calibr.	Info	Comments
1234 EXPT.ZT9A.001				1		BXSCAL_1000/StatusBean not available / Faulty / BXSCA
1234 EXPT.ZT9A.002		0.00E+00	1.00E+00	1		BXSCAL_1001/StatusBean not available / Faulty / BXSCA
1234 EXPT.ZT9A.003				1		BXSCAL_1002/StatusBean not available / Faulty / BXSCA
1234 EXPT.ZT9A.004				1		BXSCAL_1003/StatusBean not available / Faulty / BXSCA
1234 EXPT.ZT9C.001				1		BXSCAL_1004/StatusBean not available / Faulty / BXSCA
1234 EXPT.ZT9C.002				1		BXSCAL_1005/StatusBean not available / Faulty / BXSCA
1234 EXPT.ZT9C.003		0.00E+00	1.00E+00	1		BXSCAL_1006/StatusBean not available / Faulty / BXSCA
1234 EXPT.ZT9C.004				1		BXSCAL_1007/StatusBean not available / Faulty / BXSCA

Run Hold Refresh Refresh All Refresh Selected Set Calibration Factor Store to e-logbook

1234 Scalers x


1234 Triggers Status [Triggers]

Beam: ZT9 / ZT9-EXP
File: ZT9A.ZT9-EXP.567 Momentum: +15.00 GeV/c Comment: BL4S 15 GeV positive hadrons focus 10 m from XBPF 51

Triggers	Count	Normaliz...	Norm co...	Coincidence	Coinc. count	TDC count	HV	HV BeamR...	Pos	Info	Comments
ZT9.BXSCI041											BXSCINT_1002/StatusBean
ZT9.BXSCI050											BXSCINT_1003/StatusBean

Run Hold Refresh Refresh All Refresh Selected Move In Move Out Restore HV Store to e-log...

1234 Triggers x



CESAR GUI 9.7.6

Status Files Tune Detectors Access EA View Window

BEA TCH

ZT9

Threshold Status [Thresholds]

Beam: ZT9 / ZT9-EXP
File: ZT9A.ZT9-EXP.567
Momentum: +15.00 GeV/c
Comment: BL4S 15 GeV positive hadrons focus 10 m from XBPF 51

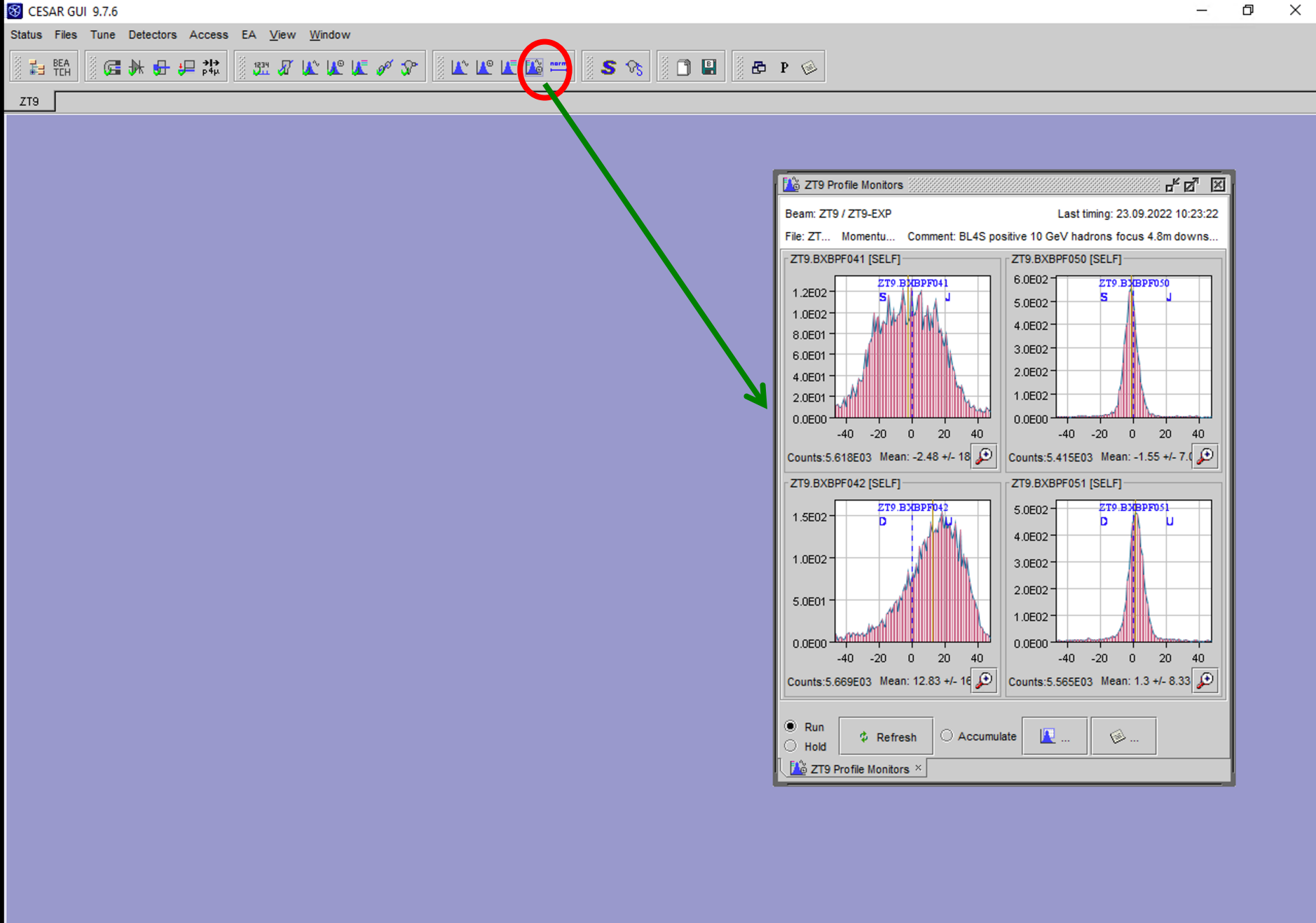
Thresholds	Pressure	HV	Coincidences	Cherenkov	Trigger	TDC Count	Gas	Info	Comments
ZT9.XCET044	0.303	-2259	0.0000E+00	2.0900E+02	1	0	carbon dioxid		
ZT9.XCET048						0	unknown		BXCET_1001/AcquisitionBeam

Run Hold Refresh Refresh All Refresh Selected Set Pressure Restore HV Store to e-logbook

Set ZT9.XCET044 Pressure

Set 0.303 Bar

OK Cancel





Allows to
access the
zone or
switch on
the Beam

ZT9 Access Command

PPEZT9 Refresh **OPEN** **BEAM ON** Cancel

DOOR STATUS

Closed
Safe

Chains connected to the door

CHAIN	SAFE
ZT9A	<input checked="" type="checkbox"/>

Doors linked to involved chain(s)

DOOR	STATUS	VETO
PPEZT9	CLOSED	<input type="checkbox"/>

Logging Console

clear

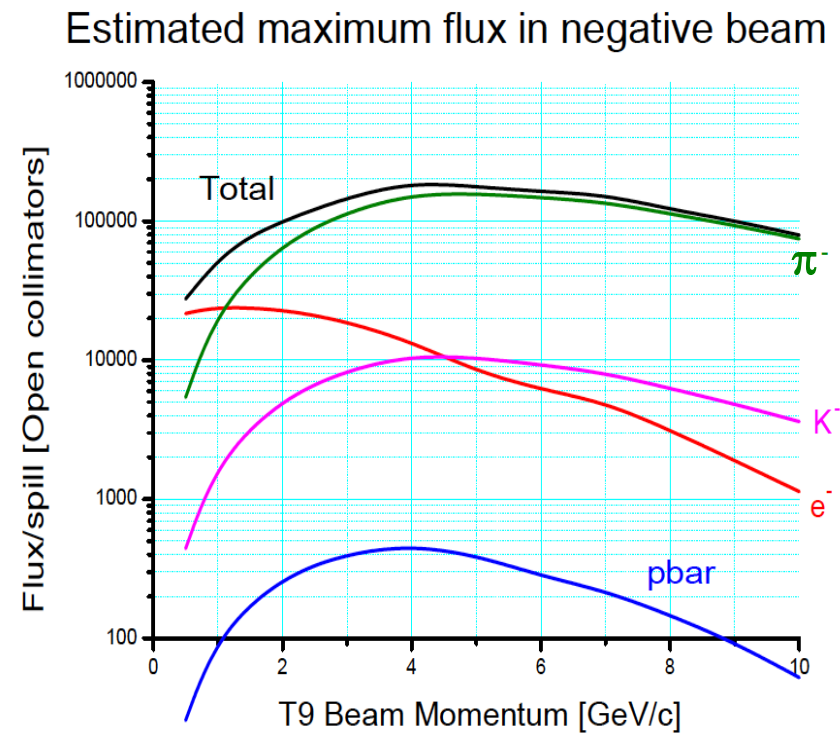
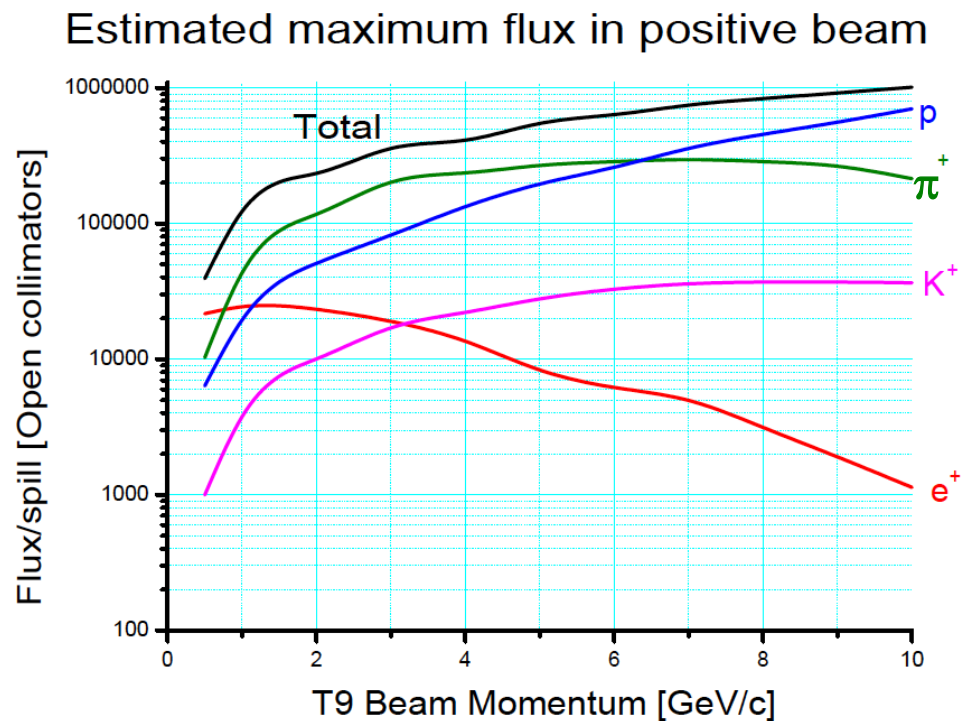
PRIMARY ELEMENTS

ELEMENT	CHAIN	VALUE	SAFE	VETOED
ZT9.TBS017	ZT9A	IN	<input checked="" type="checkbox"/>	<input type="checkbox"/>

SECONDARY ELEMENTS

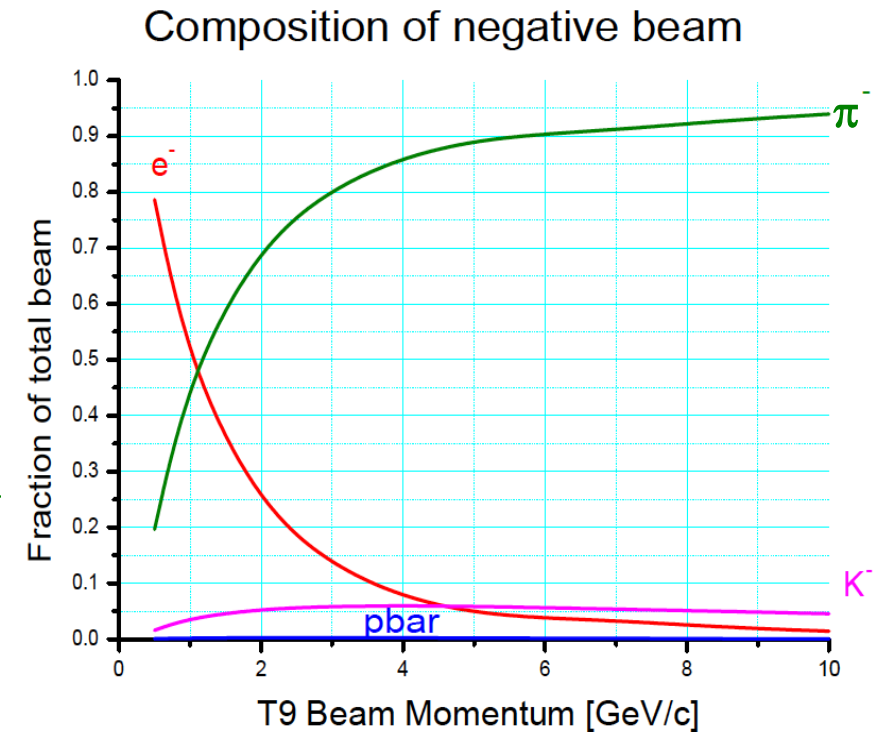
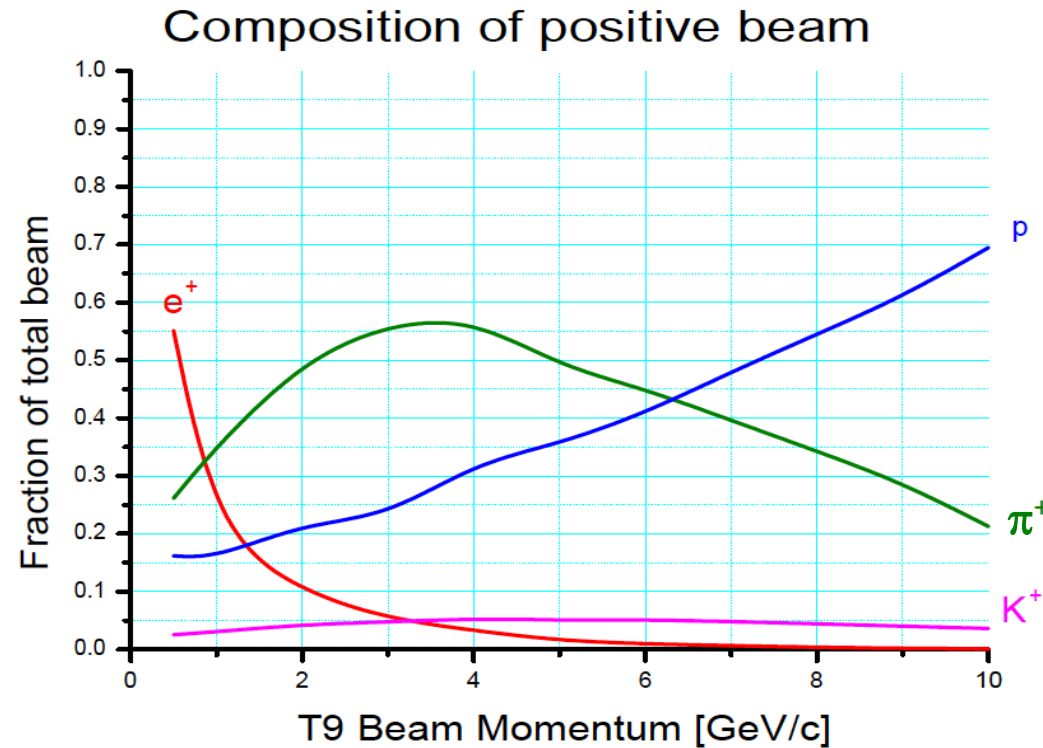
ELEMENT	CHAIN	VALUE	SAFE
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Beam rates



For wide open collimators, i.e. $dp/p \approx \pm 7.5\%$ (Theoretical Calculation)

Beam composition



With electron enriched target (otherwise e^\pm strongly reduced) (Theoretical Calculation)