The CERN Injector Complex and Beams for non-LHC Physics
Academic Training Lecture 18-06-2012

Lau Gatignon / EN-MEF
FIXED TARGET vs COLLIDERS

Fixed target physics is complementary to collider physics:

- The maximum CM energy in FT is much smaller: \( s = 2 M \cdot E_{\text{beam}}, \) hence \( E_{\text{CM}} \sim \sqrt{E_{\text{beam}}}, \)
- But a collider is restricted to the particle types accelerated and stored in the collider, whereas fixed target beams allow control over a wider range of particle types
- A collider can only house a limited number of experiments, whereas a fixed target facility can house many beam lines and experiments.
- Collider detectors are closed and as compact as possible, therefore difficult to access, whereas fixed target experiments are normally long and open, allowing easier access to the individual detectors.

In general colliders are discovery machines giving access to new energy domains and thus to new and heavy particles. Fixed target experiments are in many cases fine tuned for specific measurements, addressing e.g. very rare events or events with specific signatures, measuring specific values to great precision.

Both can give access to new and very interesting physics.
The LINACs: where it all starts.....

**Linac2: the proton source**
- Built from 1973 to 1978
- Total length: \( \sim 33 \text{ m} + 80 \text{ m} \) transfer line
- 50 MeV kinetic energy
- \( \sim 170 \text{ mA} \) protons

**Linac3: the heavy ions source**
- Commissioned in 1994
- Total length: \( \sim 12 \text{ m} + \text{short transfer line} \)
- 4.2 MeV/N
- 25 \( \mu \text{A} \) Pb\(^{54+}\)
- Preparations under way for Ar and Xe beams
A new Linac is under construction: LINAC4

<table>
<thead>
<tr>
<th></th>
<th>energy</th>
<th>current</th>
<th>Pulse length (4 rings)</th>
<th>Emittance (rms mm mrad)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>LINAC4</td>
<td>160 MeV</td>
<td>40 mA</td>
<td>400μs</td>
<td>0.3</td>
<td>Chopped, H⁻</td>
</tr>
<tr>
<td>LINAC2</td>
<td>50 MeV</td>
<td>160 mA</td>
<td>100μs</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

1. Lower emittance from the LINAC4, charge exchange injection allow for tailoring the emittance in the PSB
2. H⁻ and chopping: lossless injection
3. Longer pulse, higher energy and lower current

Ready for connection to PSB in 2015

The connection requires 8 months

Exact time tbd

Minor impact on FT beams
The PS Booster (PSB)

The PS Booster was built in 1972, Its circumference is ~157 meters (1/4 x PS).

An upgrade to 2 GeV/c is under study, as well as towards H⁻ injection from Linac4.

The PS Booster (PSB) receives the beam from Linac2 and accelerates it to 1.4 GeV/c for ejection towards ISOLDE or 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 $3.2 \times 10^{13}$.
**Radioactive Ion Beams**

Produce radioactive nuclides via spallation, fission or fragmentation in a thick target via a 1.4 GeV/c proton beam from the PSB with an intensity up to 2 µA.

The HRS (High-Resolution Spectrometer) and General Purpose Spectrometer (GPS) are two isotope separators that deliver 60 keV mass separated radioactive ion beams. The GPS has one bending magnet and can extract three beams simultaneously. The HRS extracts one beam with two dipole magnets. Together they serve a large number of experimental installations.
Research with Radioactive Ion Beams

- **Applied Physics**
  - Implanted Radioactive Probes, Tailored Isotopes for Diagnosis and Therapy
  - Condensed matter physics and Life sciences

- **Fundamental Physics**
  - Direct Mass Measurements, Dedicated Decay Studies - WI CKM unitarity tests, search for $\beta-\nu$ correlations, right-handed currents

- **Nuclear Physics**
  - Nuclear Decay
  - Spectroscopy and Reactions
  - Structure of Nuclei
  - Exotic Decay Modes

- **Atomic Methods**
  - Laser Spectroscopy and Direct Mass Measurements
  - Radii, Moments, Nuclear Binding Energies

- **Nuclear Astrophysics**
  - Dedicated Nuclear Decay/Reaction Studies
  - Element Synthesis, Solar Processes

- **Other Areas**
  - Weak Interaction and Nuclear Physics 40%
  - Particle and Astrophysics 10%
  - Solid state physics 24%
  - Biology/Medicine 4%
* Energy from 60 kV to few MeV/u
* Operational since Oct 2001
* Until now:
  >30 elements
close to 100 isotopes

**CERN Injector Complex and Beams for non-LHC physics**

**Electron beam ion source**
* 1+ ions to n+
* Super conducting solenoid, 2 T
* Electron beam <0.4 A, 3-6 keV
* Breeding time 3 to >200 ms

**Linac**
- **Type**: normal conducting
- **Length**: 11 m
- **Freq.**: 101 MHz (202 MHz for the 9GP)
- **Duty cycle**: 1 ms 100Hz
- **Energy**: 300 keV/u, 1.2-3 MeV/u (variable)
- **A/q max.**: 4.5

**Penning trap**
* Longitudinal accumulation and bunching
* Transverse phase space cooling
* 3 T solenoid field
  + quadratic electrostatic potential
  + RF cooling
* Buffer gas filled (5E-4 mbar)
* Cooling time ~20 ms
HIE-ISOLDE: A post-accelerator after REX-ISOLDE

Accelerate ions up to 10 MeV/u up to A/q = 4.5. First phase planned for 2015.
The LEIR ring accumulates ions from Linac3 for injection into the PS and from there via the SPS to the North Area or the LHC. The ion beam is cooled with strong electron cooling in order to reach the high density needed for LHC ion operation. LEIR also plays a central role in providing the ion beams for the North Area ion physics program.

The LEIR machine uses a multi-turn injection from Linac3, normally Pb$^{54+}$, but lighter isotopes are possible (e.g. Ar and Xe). They are accelerated to 72 MeV/u, then further accelerated by the PS and fully stripped before being sent to the SPS.

The LEIR circumference is about 80 m.
THE PROTON SYNCHROTRON (PS)

The Proton Synchrotron is the oldest machine at CERN, commissioned in 1959 (!), but it is still functioning well and even well beyond its initial specifications!

The PS is still vital for almost all beams at CERN and its versatility and flexibility is truly impressive.

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 has a circumference of ~628 meters and is capable to accelerate protons up to 26 GeV/c.

It operates in a cyclic mode with a basic period of 1.2 seconds. The PS super-cycle is driven by the SPS, which has recently operated with a repetitive cycle of about 45.6 seconds. Within that time the PS must serve all users, including the SPS North Area, CNGS, the LHC, the AD, the East Area, nTOF and machine studies. The proton intensities per cycle vary from $10^{11}$ ppp for DIRAC to 2-3 $10^{13}$ ppp for CNGS.
EXAMPLE OF A PS SUPER-CYCLE

Or e.g.: (part of s.c.)

The super-cycle can now be re-programmed ‘on the fly’
**SOME TYPICAL PS CYCLES**

<table>
<thead>
<tr>
<th>User</th>
<th>Momentum</th>
<th>Flat top</th>
<th>Intensity</th>
<th>Duration</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFTPRO</td>
<td>14 GeV/c</td>
<td>–</td>
<td>Up to $3 \times 10^{13}$</td>
<td>1.2 s</td>
<td>Need 2 to fill SPS *)</td>
</tr>
<tr>
<td>CNGS</td>
<td>14 GeV/c</td>
<td>–</td>
<td>Up to $3 \times 10^{13}$</td>
<td>1.2 s</td>
<td>Need 2 to fill SPS *)</td>
</tr>
<tr>
<td>LHC</td>
<td>26 GeV/c</td>
<td>–</td>
<td>$1.4 \times 10^{11}$/bunch</td>
<td>1.2 s</td>
<td></td>
</tr>
<tr>
<td>EASTA</td>
<td>24 GeV/c</td>
<td>0.4 s</td>
<td>2-3 $10^{11}$</td>
<td>2.4 s</td>
<td>For test beams T9+T10 + CLOUD</td>
</tr>
<tr>
<td>EASTB</td>
<td>24 GeV/c</td>
<td>0.4 s</td>
<td>$1.2 \times 10^{11}$</td>
<td>2.4 s</td>
<td>For DIRAC experiment</td>
</tr>
<tr>
<td>EASTC</td>
<td>24 GeV/c</td>
<td>0.4 s</td>
<td>Up to $5 \times 10^{11}$</td>
<td>2.4 s</td>
<td>For Radiation facility</td>
</tr>
<tr>
<td>TOF</td>
<td>20 GeV/c</td>
<td>–</td>
<td>$8 \times 10^{12}$</td>
<td>1.2 s</td>
<td></td>
</tr>
<tr>
<td>AD</td>
<td>–</td>
<td>–</td>
<td>$1.5 \times 10^{13}$</td>
<td>1.2 s</td>
<td>Only once per ~90 seconds</td>
</tr>
<tr>
<td>MD</td>
<td>–</td>
<td>–</td>
<td></td>
<td></td>
<td>Variable parameters</td>
</tr>
</tbody>
</table>

*) The SPS circumference is 11 times the PS one. Need 1/11th of SPS for kicker switching and 5 turns of the PS to fill one half. The so-called CT extraction takes 5 turns.
Neutrons are generated by a **pulsed** beam of 20 GeV/c protons (6 ns RMS), hitting a lead spallation target. Each pulse provides up to $8 \times 10^{12}$ protons ($\sim 25$ kJ), i.e. 6-20 kW on average. Every proton yields $\sim 300$ n. The neutrons span an energy range from the **meV** to the **GeV** region.

The neutrons are collimated and guided through an evacuated pipe of 185 m length to the experimental area, where the neutrons impinge on a sample. A number of detectors allow to detect the reaction products.
The n_TOF facility

Main features of the n_TOF:
- Proton intensity: $8 \times 10^{12}$ p/pulse
- Proton beam momentum: 20 GeV/c
- Proton pulse width: 6 ns (rms)
- High instantaneous n flux: $10^5$ n/cm$^2$/pulse
- Wide energy spectrum: $25 \text{ meV} < E_n < 1\text{ GeV}$
- Low repetition rate: < 0.8 Hz
- Good energy resolution: $\Delta E/E = 10^{-4}$

Neutron beam + state-of-the-art detectors and acquisition systems make n_TOF UNIQUE for:
- measuring radioactive isotopes, in particular actinides
- identifying and studying resonances (at energies higher than before)
- extending energy range for fission (up to 1 GeV !).
nTOF PHYSICS MOTIVATIONS

range from nuclear technology (ADS, nuclear transmutation, etc) via basic nuclear physics to nuclear astrophysics and medical applications.

Nuclear technologies
- Ang. Distrib. FF
  - $^{232}$Th, $^{237}$Np, $^{235,238}$U

Nuclear Astrophysics
- Fission
  - $^{241,242}$Pu, $^{235}$U
- Neutron capture
  - $^{58,62,63}$Ni, $^{57}$Fe, $^{236,238}$U

Medical applications
- $(n,\alpha)$
  - $^{10}$B, $^{33}$S

- Nuclear technologies
- Nuclear Astrophysics
- Medical applications
nTOF EAR2 : AN UPGRADE OF THE EXISTING FACILITY

Main advantages of EAR-2 wrt. EAR-1

- Neutron fluence increase in a factor 18-25 w.r.t. EAR-1.
- Strong reduction of the g-flash because of vertical flight path (EAR-1 is placed forwards wrt. p beam).
- Complete neutron beam width reduced by a factor of 10: increase S/B ratio for radioactive samples.

Together, these improvements will result in more accurate and faster cross-section measurements, and open the door to new physics cases at even higher neutron energies.
The Antiproton Decelerator (AD)

Antiprotons are produced from pulses of $1.5 \times 10^{13}$ protons at 26 GeV/c on an Iridium production target, followed by a magnetic horn.

The antiprotons are collected at 3.57 GeV/c. Bunch rotation allows to decrease the $\Delta p/p$ from $\pm 3\%$ to $\pm 0.75\%$. Before deceleration, further reduction of the $\Delta p/p$ as well as further reduction of transverse emittance is achieved by stochastic cooling.

The antiprotons are then decelerated to 100 MeV/c. During this deceleration, the beam is again cooled several times with stochastic and electron cooling to counteract adiabatic blow-up during the energy decrease.

The beam is fast extracted and then sent to the experiments ALPHA, ATRAP, ASACUSA, AD4/ACE and AEGIS. The $\bar{p}$ intensity is about $4 \times 10^7$ per pulse.

**The (magnificent!) physics at the AD experiments will be explained by J.Hangst later this week.**
The AD machine

For 2017
Some AD pictures
ELENA (for 2017)

- Further deceleration of pbars
- Reduce emittance (e-cooling)
- Gain ~100x in intensity for most experiments

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ELENA</th>
<th>AD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>30.4 m</td>
<td>182 m</td>
</tr>
<tr>
<td>Momentum range</td>
<td>100 – 13.7 MeV/c</td>
<td>3.57 – 0.1 GeV/c</td>
</tr>
<tr>
<td>Energy range</td>
<td>5.3 – 0.1 MeV</td>
<td></td>
</tr>
<tr>
<td>Intensity injected beam</td>
<td>3.10^7</td>
<td>5.10^7</td>
</tr>
<tr>
<td>Intensity ejected beam</td>
<td>1.8.10^7</td>
<td>3.10^7</td>
</tr>
<tr>
<td>Nr. extracted bunches</td>
<td>1 to 4</td>
<td>1</td>
</tr>
<tr>
<td>Transv. emit. at 100 keV</td>
<td>4 / 4 μm</td>
<td>5 π μm</td>
</tr>
<tr>
<td>Bunch length at 100 keV</td>
<td>1.3 m / 300 ns</td>
<td>~200 ns</td>
</tr>
</tbody>
</table>

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The CERN Injector Complex and Beams for non-LHC physics
The East Area (PS)
The East Area Beams
(Schematic view!)

T7 beam
(not used)

T9 beam
12 (15) GeV/c

T10 beam
6 GeV/c, 60 mr

DIRAC

IRRAD

EASTA

EASTB

EASTC

DIRAC

EASTA

EASTB

EASTC

IRRAD

T11: 3.6 GeV/c, 150 mrad

N-target

S-target

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The CERN Injector Complex and Beams for non-LHC physics
The CERN Injector Complex and Beams for non-LHC physics
THE T8 BEAM LINE

The T8 beam line serves the DIRAC experiment (→ G. Mallot lecture).

It is a primary proton beam of 24 GeV/c slowly extracted over a flat top of 400 or even up to 600 msec. For a 45.6 sec super-cycle up to five EASTB (T8) cycles can be scheduled, depending on the requirements of the overall program. The T8 intensity is normally in the range 1-5 \(10^{11}\) ppp typically 1.1 \(10^{11}\) for DIRAC).

The beam is de-bunched. The spot size at DIRAC is ~5 mm RMS.

It is foreseen to dismount DIRAC in 2013 and to move the IRRADiation facility into the T8 line. The required beam characteristics are the same, apart from the higher beam fluxes (up to ~5 \(10^{11}\) ppp). The new facility will include a proton irradiation facility plus a mixed field facility. The existing IRRADiation facilities on the T7 side and behind DIRAC will be dismantled.
THE PROPOSED IRRADIATION FACILITY (by R2E + AIDA)

Mixed Field Facility
- multiple user communities: LHC machine, LHC Experiments, Dosimetry (RP), MC benchmarking
- rail system on floor for heavy material, shuttle system or small rail system on ceiling (?)

Proton Facility
- main user community: LHC Experiments
- Irradiation tables
- Cold boxes
- Shuttle system

Layout IRRAD Tables System

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The CERN Injector Complex and Beams for non-LHC physics
The Beam Line for CLOUD

Intensity: up to $10^6$ ppp
Flat top 0.4 sec (up to 3x / s.c.)
Maximum momentum 3.6 GeV/c
Beam spot $\sim 1.6 \times 1.6$ m$^2$
Climate forcings (IPCC 2007)

- 0.7°C rise since 1900 (not uniform)
- IPCC findings:
  - Total anthropogenic 1.6 W/m²
    \( \approx 1 \text{ candle per } 25 \text{ m}^2 \)
  - Negligible natural (solar) contribution: 0.12 W/m²
  - Clouds poorly understood
East Area Test Beams

The T9 and T10 beam lines are mixed beams. Their maximum flux is $10^6$ per EASTA cycle. Both beams are served from a common target, together also with the T11 beam for CLOUD. The flat top is 0.4 seconds. The number of EASTA cycles is defined by the physics coordinator, depending on the overall schedule, but is normally 1 per super-cycle. When CLOUD runs up to 3.

Each beam line is equipped with 1 (T10) or 2 (T9) threshold Cerenkov counters, a scintillator and a Delay wire chamber.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>T9</th>
<th>T10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum momentum (GeV/c)</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>Production angle (mrad)</td>
<td>0</td>
<td>61.6</td>
</tr>
<tr>
<td>Beam length to ref. focus (m)</td>
<td>55.8</td>
<td>34.9</td>
</tr>
<tr>
<td>Beam height above floor (m)</td>
<td>2.50</td>
<td>2.505</td>
</tr>
<tr>
<td>Ang.acceptance Horiz (mrad)</td>
<td>±4.8</td>
<td>±5.4</td>
</tr>
<tr>
<td>Vertic (mrad)</td>
<td>±5.8</td>
<td>±13.9</td>
</tr>
<tr>
<td>Acc. Solid angle (μsterad)</td>
<td>87</td>
<td>224</td>
</tr>
<tr>
<td>Theor. momentum resol. (%)</td>
<td>0.24</td>
<td>0.24</td>
</tr>
<tr>
<td>Max. momentum band (%)</td>
<td>±10</td>
<td>±8</td>
</tr>
<tr>
<td>Magnification at ref. focus</td>
<td>1.0, 1.2</td>
<td>0.8, 0.6</td>
</tr>
<tr>
<td>Protons on North target</td>
<td>~2.5 $10^{11}$</td>
<td></td>
</tr>
<tr>
<td>Max. flux (depending on p, Q)</td>
<td>$10^6$</td>
<td>$10^6$</td>
</tr>
</tbody>
</table>
THE PROPOSED EAST AREA UPGRADE

An upgrade and consolidation program has been proposed for the East Area. A first phase is foreseen in this year’s MTP and includes as a first phase the upgrade of the IRRADiation facilities and some preparation works. Most of the upgrade, if approved, will happen in/after LS2.

The main parts of the new layout include:

- Suppress the old T7+IRRAD branch
- **Move IRRAD to T8 beam line**
- Increase top momentum of T9 to 15 GeV/c and T10 to 12 GeV/c (overlap with SPS beams)
- Implement control over particle type: e / h / μ
- Study option to preserve T11, if not realistic move CLOUD to downstream end of T9
- Use fewer types of magnets (with spares) which are reliable and maintainable
- **Improve RP aspects** of zone: stop protons soon after production target, ventilation, ....
- Improve access to beam line elements
- Improve infrastructure in general
CONCEPT:

GENERIC NEW EAST AREA TEST BEAM OPTICS

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The CERN Injector Complex and Beams for non-LHC physics
THE SUPER PROTON SYNCHROTRON (SPS)

The Super Proton Synchrotron is the last accelerator in the injector chain before the LHC. Its 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 ($t_{\text{rev}} = 23$ µsec). The PS fills one half of the SPS in a 5-turn extraction, the second half 1.2 seconds later. One eleventh of the machine is reserved for switching the injection kicker on and off. The protons are injected at 14 GeV/c and (nowadays) accelerated to 400 GeV/c. At the end of acceleration $\Delta p$ is maximised, the RF switched off (→debunching!) and the beam slowly extracted over a 9.6 s flat top to the North Area. Alternatively the beam can be extracted in two shots of ~10 µsec each (separated by 50 msec) to the CNGS target.
The SPS has gradually been transformed into a multi-cycling machine. The super-cycle can be re-programmed (almost) on the fly. The addition of CNGS and LHC filling cycles had lead to very long super-cycles:

The white curve indicates the current in the main SPS dipoles. The yellow curve indicates the proton intensity in the ring. The blue curve is the same for lower beam intensities where a larger gain factor is used.

The maximum intensity per SPS cycle that can be extracted to the North Area or to CNGS is of the order of $4 \times 10^{13}$ ppp. This corresponds to a total energy of 2.5 MJ!

The beam to the NA is split into 3 branches, serving 3 primary targets.
SHORT VS LONG FLAT TOP

For most experiments the statistics depends on integrated “time on flat top”, hence on the **duty cycle**. Up to 2007, the duty cycle was ~30%, e.g. 4.8 sec FT per 14.4 or 16.8 sec.

The addition of CNGS cycles in the super-cycle would have lead to a reduction of duty-cycle for the fixed target program in the North Area. The introduction of a longer flat top has mitigated the effect to a large extent.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 1999</td>
<td>450</td>
<td>2.4</td>
<td>14.4</td>
<td>FT limited by heating</td>
</tr>
<tr>
<td>2000 - 2007</td>
<td><strong>400</strong></td>
<td>3.2- <strong>4.8</strong></td>
<td>14.4 – 16.8</td>
<td>To have better duty cycle</td>
</tr>
<tr>
<td>2008-now</td>
<td>400</td>
<td>9.6</td>
<td>~ 45.6</td>
<td>CNGS (+LHC filling)</td>
</tr>
<tr>
<td>After LS1</td>
<td>400</td>
<td>Yet to be defined</td>
<td></td>
<td>E.g. depending on CNGS future</td>
</tr>
</tbody>
</table>

For most experiments the statistics depends on integrated “time on flat top”, hence on the **duty cycle**. Up to 2007, the duty cycle was ~30%, e.g. 4.8 sec FT per 14.4 or 16.8 sec.

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NORTH AREA BEAM LINES
(Schematic view!)

T2 wobbling

T4 wobbling

P42

K12

P6

M2

NA62

COMPASS

NA61

H2

H4

H6

H8

T2

T4

T6

T10

Cedar

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The CERN Injector Complex and Beams for non-LHC physics
### THE BEAM LINES IN EHN1

<table>
<thead>
<tr>
<th>Beam</th>
<th>Momentum</th>
<th>Particle types</th>
<th>#Zones</th>
<th>Expts</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2</td>
<td>≤ 400 GeV/c</td>
<td>p, e, h, μ, ions*)</td>
<td>2</td>
<td>NA61*)</td>
<td>One zone reserved for NA61.</td>
</tr>
<tr>
<td>H4</td>
<td>≤ 450 GeV/c</td>
<td>p, e, h, μ, ions*)</td>
<td>4</td>
<td>NA63</td>
<td>One zone is dedicated to H4IRRAD.</td>
</tr>
<tr>
<td>H6</td>
<td>≤ 205 GeV/c</td>
<td>e, h, μ</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H8</td>
<td>≤ 450 GeV/c</td>
<td>p, e, h, μ, ions*)</td>
<td>4</td>
<td>UA9-T</td>
<td>One zone is dedicated to UA9-T. Micro-beam option for primary p. No electrons from γ conversion</td>
</tr>
</tbody>
</table>

The maximum fluxes depend strongly on the momentum, charge, particle type, production angle, layout, shielding, equipment installed on the beam and on the access possibilities to the zones downstream. Constrained by radio-protection requirements!. Typical fluxes are in the $10^5$ to $10^6$ per pulse range, but under certain conditions higher fluxes can be provided.

Please note that there is a coupling between beam lines from the same target: **Wobbling**

*) Up to LS1, only fragmented ion beams can be provided
After PS1, primary Pb, Ar and Xe beams are possible
THE T2 WOBBLING STATION

The CERN Injector Complex and Beams for non-LHC physics
THE T4 WOBBLING STATION

The CERN Injector Complex and Beams for non-LHC physics
FLEXIBILITY IN EHN1 BEAMS

The Wobbling system in rich in options, but each change affects at least 2 beam lines. Extra flexibility is provided by:

- Tertiary beams
- Electron beams from $\gamma$ conversion: Use Pb converter
- Hadron beams from $K^o$ and $\Lambda$ decay (T2 beams only): no converter
- Muons only by stopping the hadrons (and electrons) in a collimator or dump

**Primary Target (Be)**

**Primary beam**
400 GeV/c $p$
Few $10^{12}$ ppp

**Secondary Target**

**Secondary beam**
Mixed ($e+h+\mu$)
Typically ~100 GeV/c
Flux ~ $10^7$ ppp

**Absorber**
(few mm Pb)

**Tertiary beam**
Typically 10-80 GeV/c
Flux up to $10^4$ ppp, e.g.

- ~4 mm Pb: 1$X_o$, $<1\lambda_i$; ‘pure’ electrons
- ~40 cm Cu: 3$\lambda_i$, ~30 $X_o$: hadrons

**Also:**

**Sweeper**
$\gamma$, $K^o$, $\Lambda$, n

**Converter (few mm Pb):**

**B1**

IN: beam mostly electrons
OUT: mostly $\pi$ or $p$ from $K^o$
or $\Lambda$ decay

Lau Gatignon, 18 June 2012
The CERN Injector Complex and Beams for non-LHC physics
FRAGMENTED ION BEAMS FOR NA61

The NA61 experiment will scan a wide parameter space with different beam energies and ion species. However, any ion species needs very long setting-up time (many months) and therefore in each year the LHC and the SPS fixed target program must use the same primary ion species, normally Pb$^{82+}$. In 2014 the SPS and the LHC will use primary Ar$^{18+}$ ion beams, in 2015 Xe$^{54+}$, later again (primary) Pb$^{82+}$. In the other years light ion beams can be produced by fragmentation of fully stripped Pb$^{82+}$ beams.

![Diagram of fragmentation process]

\[
\text{e.g.: } 400 \text{ GeV/c} \rightarrow (82/208) \times 400 = 158 \text{ GeV/N} \quad \quad 158 \text{ GeV/N} \rightarrow (8/4) \times 158 = 316 \text{ GeV/c}
\]

The exact factor to be applied depends on the isotope selected. With the addition of a degrader in the beam line a sufficient rigidity resolution is obtained to achieve pure beams of light ion species. Unfortunately purity and intensity become marginal for the heavier species, where primary beams must be used instead.
The target (18 cm Be) initiates the fragmentation. The target is followed by a first stage of rigidity selection (A/Z). However, the resolution is limited due to Fermi motion and scattering inside the target.

In the degrader the surviving ions loose energy \( \sim Z^2 \). The second stage of the beam line takes this dE/dx into account to refine the final fragment selection.

**The Z-selection**

- **without degrader**

- **with degrader**
THE M2 MUON BEAM
FOR COMPASS / NA58

Up to $2 \times 10^8 \mu^+/\text{cycle}$

$p_{\text{max}} = 190 \text{ GeV/c}$
THE MUON AND HADRON BEAMS FOR COMPASS

The M2 beam line is ~ 1200 m long from the T6 production target to the end of the EHN2 hall.

It can be operated in three different modes:

• As a high-energy, high-intensity muon beam. Normally for muon momenta up to 200 GeV/c. Higher momenta are in theory possible, but the flux drops very rapidly with beam momentum.
• As a high-intensity secondary hadron beam for momenta up to 280 GeV/c
• As a low-energy, low-intensity (and low-quality) in-situ electron calibration beam.

The main parameters are listed in the table below:

<table>
<thead>
<tr>
<th>Beam Mode</th>
<th>Momentum (GeV/c)</th>
<th>Max. Flux (ppp)</th>
<th>Typical Δp/p (%)</th>
<th>Typical RMS spot at target</th>
<th>Polarisation</th>
<th>Absorber (9.9 m Be)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muons</td>
<td>+208/190 +172/160</td>
<td>~2 $10^8$ 4.5 $10^8$</td>
<td>3%</td>
<td>8 x 8 mm</td>
<td>80%</td>
<td>IN</td>
</tr>
<tr>
<td>Hadrons</td>
<td>+190 -190 Max. 280</td>
<td>$10^8$ (RP)</td>
<td>-</td>
<td>5x5 mm</td>
<td>-</td>
<td>OUT</td>
</tr>
<tr>
<td>Electrons</td>
<td>-10 to -40</td>
<td>&lt; 2 $10^4$</td>
<td>-</td>
<td>&gt; 10x10 mm</td>
<td>-</td>
<td>OUT</td>
</tr>
</tbody>
</table>

Each mode has its own optics definition. The hadron mode has a parallel section with 2 Cedars.
EHN2: COMPASS
NA62 Beam & Detectors

SPS primary p: 400 GeV/c
Unseparated beam:
- 75 GeV/c
- 750 MHz
- \(\pi/K/p\) (~6% \(K^+\))

K\(^+\) → \(\pi^+\) νν
Main design consideration for new K12 beam for NA62:

• **High intensity $K^+$ beam** for the very rare decay mode $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ (B.P. $\sim 10^{-10}$)

• Momentum: 75 GeV/c because close to maximum $K^+$ flux.

• Carefully **matched to hermeticity of NA62 veto system**, which assumes $15 < p_\pi < 35$ GeV/c. The veto system must detect a missing energy of at least 40 GeV with extremely high efficiency. Beam size and trajectory must therefore fit very finely with detector acceptance.

• The beam momentum is defined by a first ‘achromat’ section of 4 dipoles and a pair of ‘TAX’ dump collimators. The momentum and direction of each individual particle is measured (at almost 1 GHz rate) in a second achromat.

• A parallel section has been included in the design to house a modified **CEDAR Cerenkov counter** to tag the $K^+$ component in the beam ($\sim6\%$).

• A **radiator** allows to strongly reduce the positron component in the beam

• A **magnetic collimation system**, combined with optimised layout of return fields in the momentum measurement section allows to minimise muon backgrounds into the apparatus.

• The beam line geometry is adapted to accommodate for a **spectrometer** in the experiment.

• At the end of the beam line the charged beam is separated further from the neutral to allow vetoing against neutral particles on-axis.
The CERN Injector Complex and Beams for non-LHC physics
<table>
<thead>
<tr>
<th>Beam Experiment</th>
<th>K12K+K- NA48/2</th>
<th><strong>K12HIKA+ NA62</strong></th>
<th>Comparison FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPS Protons per s of spill length</td>
<td>( \sim 2 \times 10^{11} )</td>
<td>( 0.7 \times 10^{12} )</td>
<td>3.0</td>
</tr>
<tr>
<td>Instantaneous Proton Rate per effective s</td>
<td>( 3.3 \times 10^{11} )</td>
<td>( 1.1 \times 10^{12} )</td>
<td></td>
</tr>
<tr>
<td>SPS Duty Cycle (s / s)</td>
<td>4.8/16.8 = 0.29</td>
<td>( \sim 0.3 )</td>
<td></td>
</tr>
<tr>
<td>Effective Duty Cycle (s / s)</td>
<td>( \sim 0.18 )</td>
<td>( \sim 0.2 )</td>
<td>( \sim 1.1 )</td>
</tr>
<tr>
<td>Beam Acceptance ( x_0, y_0 ) (mr)</td>
<td>( \pm 0.36, \pm 0.36 )</td>
<td>( \pm 2.7, \pm 1.5 )</td>
<td></td>
</tr>
<tr>
<td>Solid Angle (( \mu )sterad)</td>
<td>( \approx 0.4 )</td>
<td>( \approx 12.7 )</td>
<td>32</td>
</tr>
<tr>
<td>Mean ( K^+ ) Momentum ( &lt;p_K&gt; ) (GeV/c)</td>
<td>60</td>
<td>75</td>
<td>( K^+ ) 1.4</td>
</tr>
<tr>
<td>Momentum Band:</td>
<td></td>
<td></td>
<td>( \pi^+ ) 1.5</td>
</tr>
<tr>
<td>- Effective ( \Delta p/p ) (%)</td>
<td>( \pm 5 )</td>
<td>( \pm 1.65 )</td>
<td>0.33</td>
</tr>
<tr>
<td>- r.m.s. ( \Delta p/p ) (%)</td>
<td>( \approx 3.7 )</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>r.m.s. Divergence: ( x', y' ) (mr)</td>
<td></td>
<td>( x= \pm 27.5, y= \pm 11.4 )</td>
<td>( \approx 980 )</td>
</tr>
<tr>
<td>at CEDAR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 r.m.s. Beam Size (mm)</td>
<td>( r= \sim 15 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area at KABES [4]/ GTK 3 (mm(^2))</td>
<td>( \sim 700 )</td>
<td></td>
<td>( \sim 980 )</td>
</tr>
<tr>
<td>r.m.s. Divergence: ( x', y' ) (mr)</td>
<td>( \approx 0.05, 0.05 )</td>
<td>( 0.09, 0.10 )</td>
<td></td>
</tr>
<tr>
<td>Decay Fiducial Length: (m)</td>
<td>50</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>( \Delta z (\tau_{K^+}) )</td>
<td>0.111</td>
<td>0.107</td>
<td></td>
</tr>
<tr>
<td>Decay Fraction: 1 - ( e^{-\Delta z} )</td>
<td>0.105</td>
<td>0.101</td>
<td>0.96</td>
</tr>
<tr>
<td>Inst. Beam Rate / s (MHz): ( p )</td>
<td>2.9</td>
<td>173</td>
<td>60</td>
</tr>
<tr>
<td>( K^+ )</td>
<td>1.0</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>( \pi^+ )</td>
<td>11.1</td>
<td>525</td>
<td>47</td>
</tr>
<tr>
<td>( e^+, \mu^+ )</td>
<td>( \sim 3 ), ( \sim 0.13 )</td>
<td>( \sim 0.3 ), ( \sim 6 )</td>
<td>( \sim 0.1 ), ( \sim 45 )</td>
</tr>
<tr>
<td>Total</td>
<td>( \sim 18 )</td>
<td>750</td>
<td>( \sim 42 )</td>
</tr>
</tbody>
</table>
TCC8 (where the K12 beam is being installed) in fall 2011
HiRadMat

The HiRadMat facility is a new facility at CERN, designed to provide high-intensity pulsed beams to an irradiation area where material samples and accelerator components can be tested under the effect of pulsed beams. It uses a 440 GeV/c proton beam with a pulse length of 7.2 µsec with a maximum pulse energy of 3.4 MJ.

The facility is located in the old WANF target cavern near the West Area. It uses the same extraction channel as the TI2 transfer line to the LHC. The facility is designed for a maximum of $10^{16}$ protons per year, distributed among ten experiments. It is thus not intended to accumulate large doses.
Preparing for experiments

- Interface table for installation of experiments
- Remote operations
The CERN Neutrino Beam (CNGS)
The CERN Injector Complex and Beams for non-LHC physics

CNGS Layout

Proton beam to Target Horn to Helium bags to Pion/Kaon Decay tube to Hadron stop to Muon detectors

TBID (multiplicity)

\[ p + C \rightarrow \text{(interactions)} \rightarrow \pi^+, \ K^+ \rightarrow \text{(decay in flight)} \rightarrow \mu^+ + \nu_\mu \]
The pion collection system

![Diagram of pion collection system]

Legend:
- Protons
- Cible
- CORNE 1
- CORNE 2 (réflecteur)
- Tube à vide (tunnel de désintégration)
- P_{OSC}^* \sigma_{TCC} (arbitrary units)
- \nu -fluence

Lau Gatignon, 18 June 2012
The CNGS target
- Internal conductors: parabolic shape, only 1.8 mm thickness to minimize absorptions/reinteractions but sufficient for mechanical stability
- No material in between inner/outer conductor!
FUTURE PLANS FOR NEUTRINOS

Ideas exist for future neutrino beams, in particular a short baseline on the Prevesin site at CERN, based on an extraction from the SPS.

Both a near and far detector, as well as possibly an intermediate detector, are foreseen in a recent proposal to the SPSC presented by Carlo Rubbia.

This project is still in the early phases of discussion and nothing is approved yet. In the following slide we just show one option, but alternative options are also under study.
SHORT BASELINE NEUTRINO BEAM IN THE SPS NORTH AREA

Layout parameters

- primary beam: 100 GeV, v-beam: ~2 GeV
- target station at the TCC2 level (~11m underground)
  - Lateral distance defined by the location of the near&far detectors
  - sufficient distance from TCC2 to allow works during NA operation

- not really mandatory but better if we can, at least for civils
  - cavern design like NuMI (LBNE)

- decay pipe: 80m, 3m diameter
- beam dump: 15m of Fe with graphite core, followed by μ stations
- v-beam angle: pointing upwards
  - at ~3m in the far detector → ~5 mrad slope
With present technology high energy $e^+e^-$ colliders become increasingly long, expensive and difficult.

Plasma e- beam or laser driven wakefield acceleration are being pursued in various laboratories as a way to achieve significantly higher gradients. However, for a multi-TeV linear collider a large number of accelerating stages would be required. Proton driven plasma wakefield acceleration, using a high-energy proton beam as driver, has been suggested as an alternative.

Recently a Letter of Intent has been submitted to the SPSC, which received significant interest. Very preliminary studies for building a test facility at CERN are under way. Such a facility could profit from the existing extraction for TI2 and HiRadMat in the West Area.
PPWA TEST FACILITY

Schematic layout
PDPWA experiment
(not to scale)

Underground installations
Switch... (50m)
p beam
(LHC injection type, 400 - 450 GeV)

TT61 tunnel
6-7 % slope

HiRadMat (Completion Sep 2011)

TT4 (70 m)
TT5 (50 m)

Plasma cell (5 - 20 m)

TT laser lab
Laser Plasma Injector (1 GeV, fs)
e beam inj. (10-20 MeV)

Other tests
{compact electron test beam, ...}
PDPWA
Spectromter
Beam dump

Example: Proton driven plasma structure

\[ E_x \text{ GeV/m} \]
\[ n_\varphi 10^{13} \text{ cm}^3 \]

~ 600 m total footprint

Lau Gatignon, 18 June 2012

The CERN Injector Complex and Beams for non-LHC physics
FINAL REMARKS

CERN has an active fixed target physics programme.

This programme is complementary to the collider physics experiments.

One studies subtle effects with detectors that in many cases are optimised for specific physics measurements (therefore often very elegant!). The details of many of the experiments will be addressed in the remaining lectures in this series.

These experiments are indeed smaller than the experiments at the LHC, but they nevertheless occupy up to 250 physicists and can take up to 20 years from conception/proposal to final results!

These experiments are served by a large complex of beam lines, which are interesting on their own!
ACKNOWLEDGEMENTS

Many thanks to


for their contributions and suggestions.
Horizontal:

Vertical:

The CERN Injector Complex and Beams for non-LHC physics
HALO REDUCTION IN THE MUON BEAM

A typical feature of muons is that they traverse material rather easily. Classical collimation is not useful in a μ beam. Therefore a scheme with magnetic collimation has been applied, based on toroids. The beam is equipped with 9 SCRAPERS (5 m long each) and 4 MIBS (3.2 to 8 m long). The large length is required to minimise the scattering effect of the yoke (~ √L) w.r.t. the magnetic deflection, which is proportional to L.
The Lecture Series

This is the first out of a series of 4 lectures covering the fixed target physics program at CERN.

The other lectures are:

• **QCD and Hadron Physics**  Gerhard Mallot  Wednesday
• **Flavor / Neutrino Physics**  Augusto Ceccucci  Thursday
• **Antimatter (H at AD)**  Geoffrey Hangst  Friday

The following lectures take place in the PS amphitheater 6-2-024