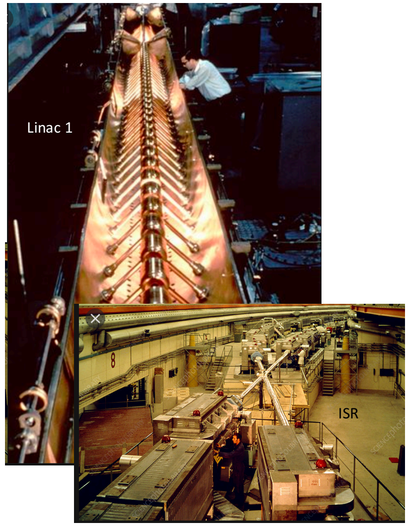
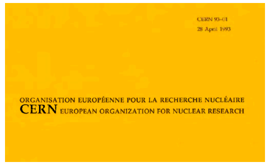
Preparing the CERN Ion Injector Chain for an LHC Oxygen Run

- Brief introduction about the history of ions at CERN
- The ion accelerator complex
- Oxygen charge and beam intensities across the complex
- Overview of what has been done and what remains to be done





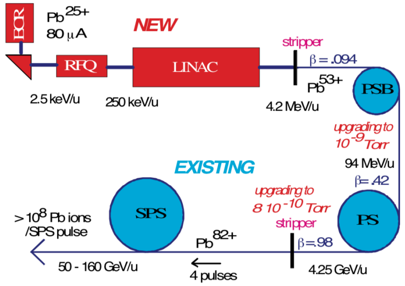


Fig. 1: Layout of the CERN Heavy Ion Accelerating Facility

2 O4+ injections in LEIR + capture + acceleration

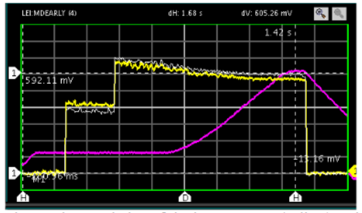
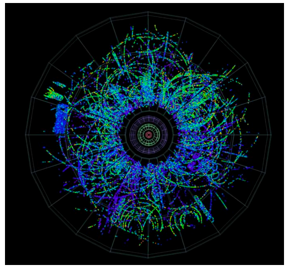
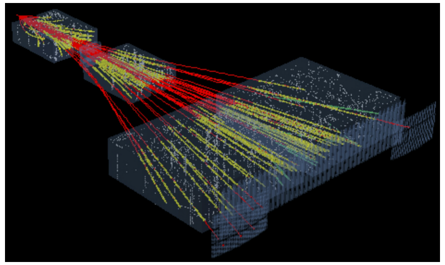


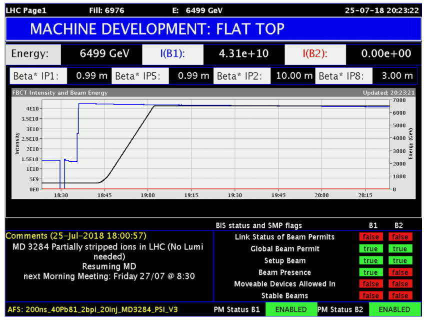
Fig. 4: Time evolution of the beam current (yellow) and the magnetic cycle (purple).

pPb pilot run



Ar on Sc NA61/SHINE



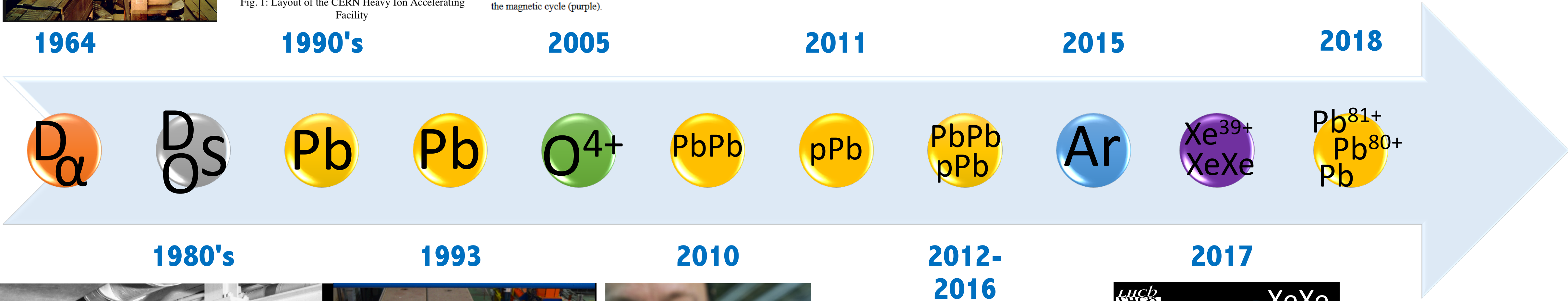


SCIENCE / PHYSICS

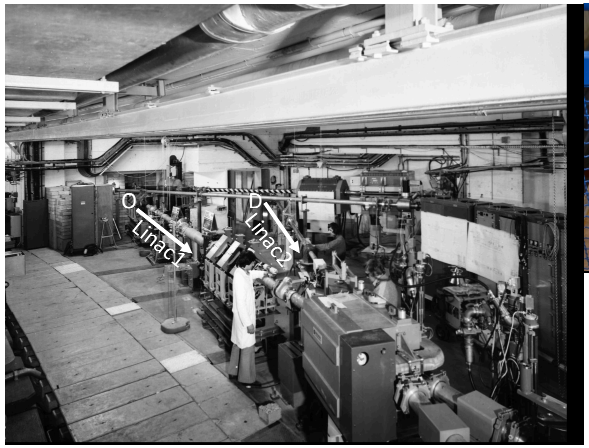
CERN's Large Hadron Collider Accelerates its First 'Atoms'

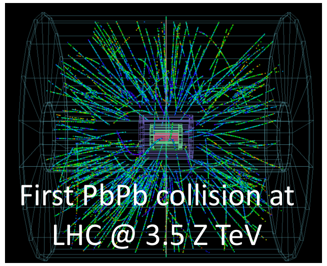
Physicists from CERN spent a few special days testing the possibilities of transforming the LHC into a gamma ray factory.

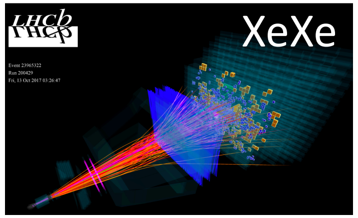
1964 **1990's** **2005** **2011** **2015** **2018**



1980's **1993** **2010** **2012-2016** **2017**



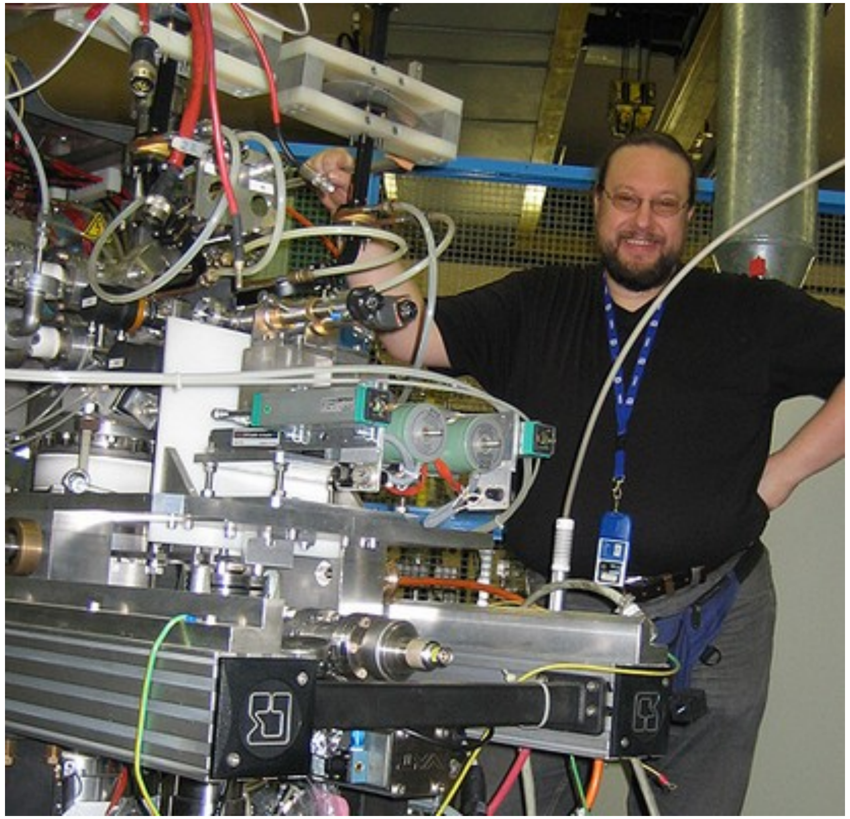




Partially stripped ions

Pb Ion source

Small sliver of solid and isotopically pure 208Pb is placed in a ceramic crucible that sits in an "oven"



The metal is heated to around 800°C and ionized to become plasma. Ions are then extracted from the plasma and accelerated up to 2.5 keV/nucleon Pb29+.

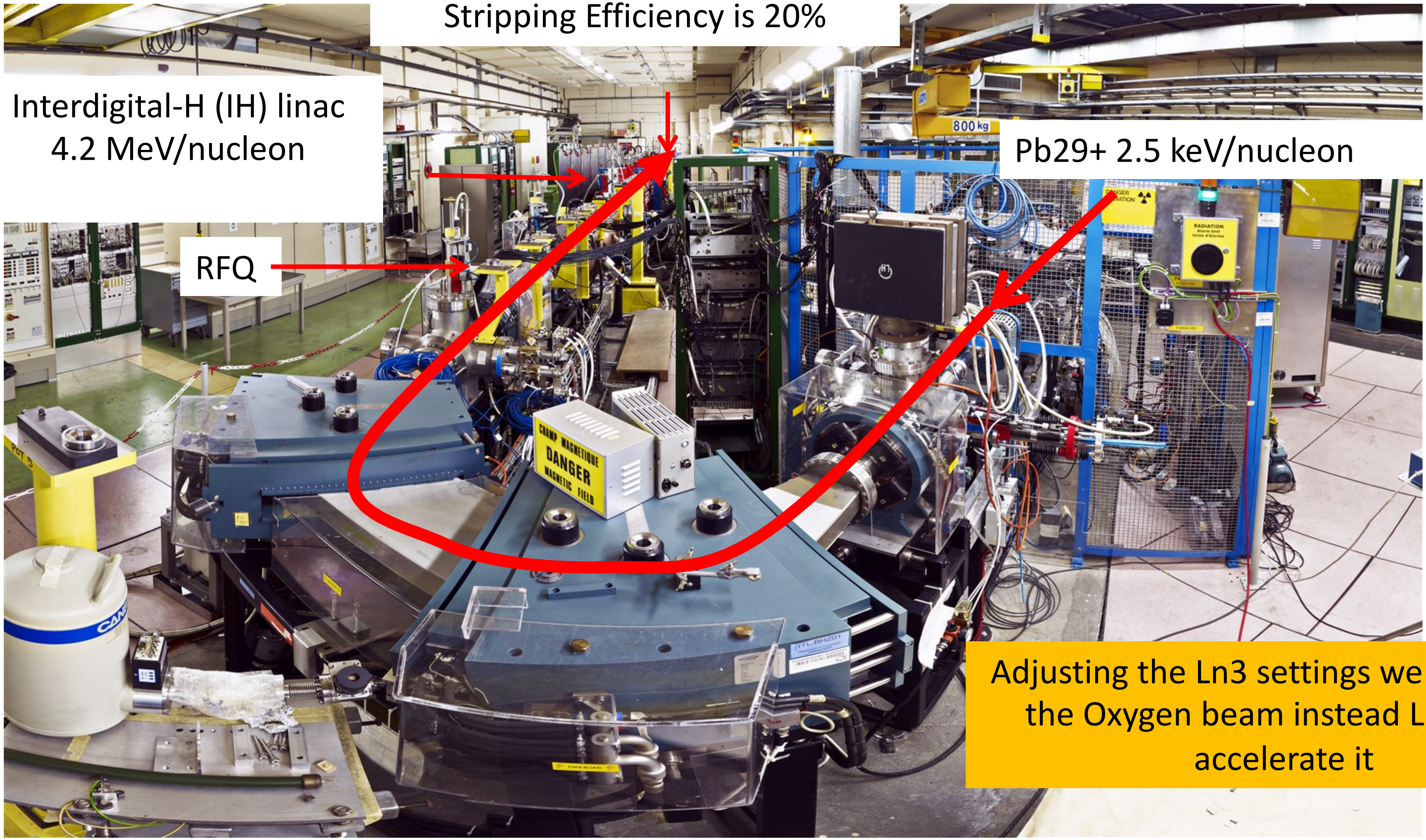
The source can also be set up to deliver other species… Ar, Xe, etc and O

Oxygen is a support gas for Pb! So we get if for free

LINAC3

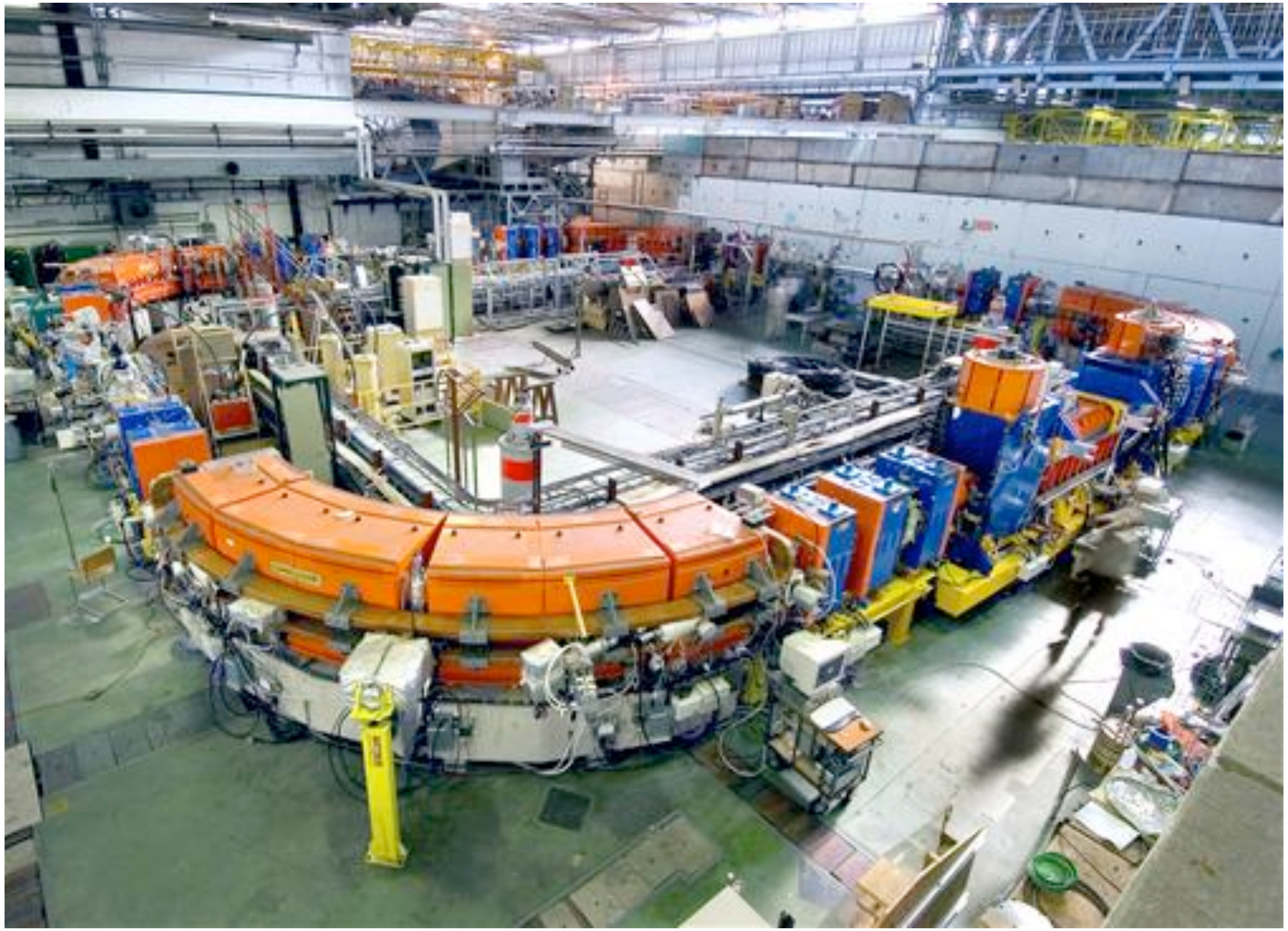
Oxygen won't be stripped

Stripping foil **Pb29+ ➔ Pb54+**
Stripping Efficiency is 20%



Adjusting the Ln3 settings we can select the Oxygen beam instead Lead and accelerate it

Low Energy Ion Ring (LEIR)



LEIR **accumulates** and **cools down** the 200 µs pulses from Linac3

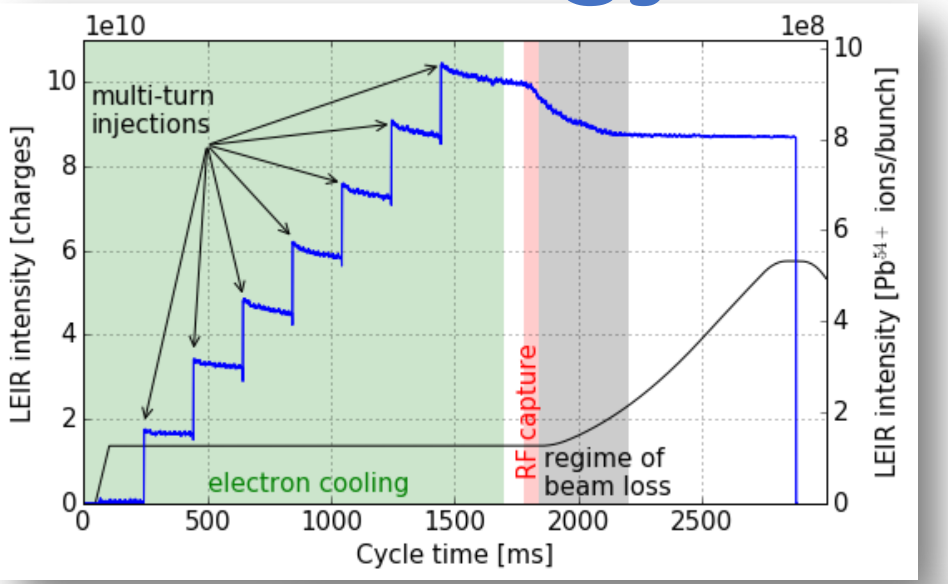
Electron Cooling is used to achieve the required brightness

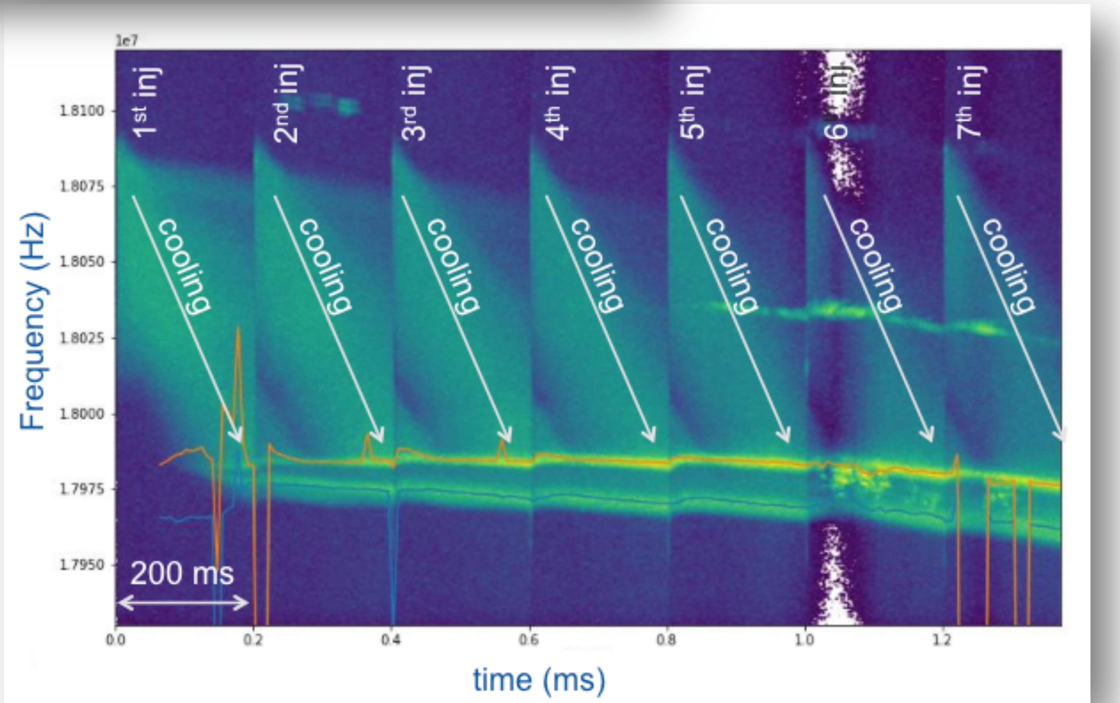
After injection, the e-cooler is switched off and the RF system is switched on to **capture** the DC beam in two bunches.

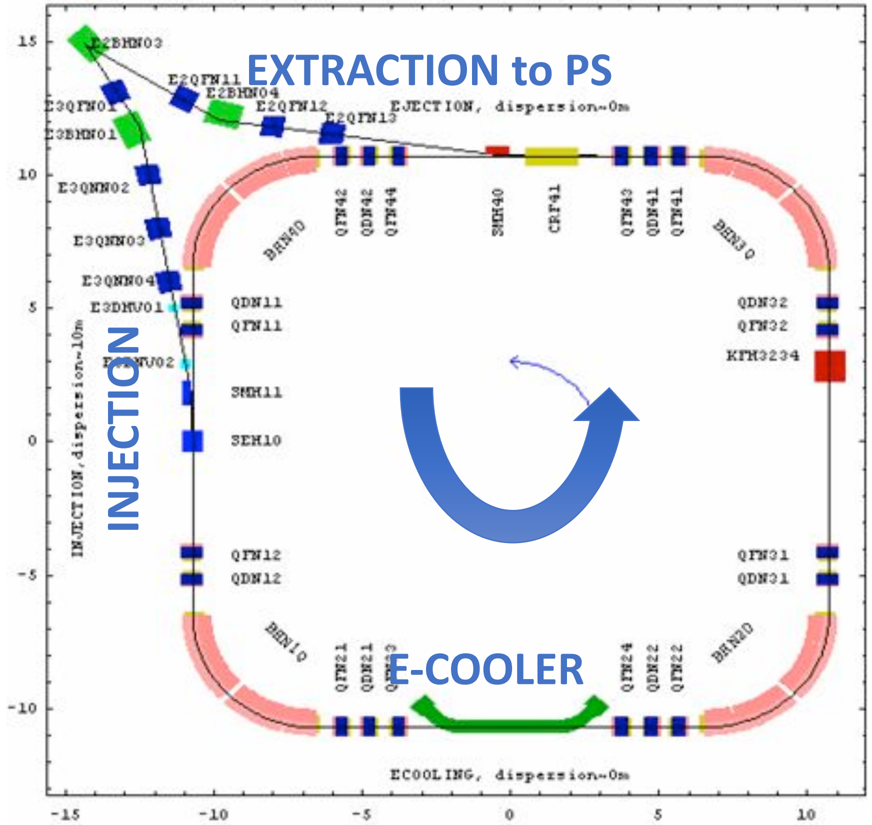
Acceleration to 72 MeV/nucleon before transfer to the PS

LEIR NOMINAL Cycle for LHC is 3.6 s

Low Energy Ion Ring (LEIR)



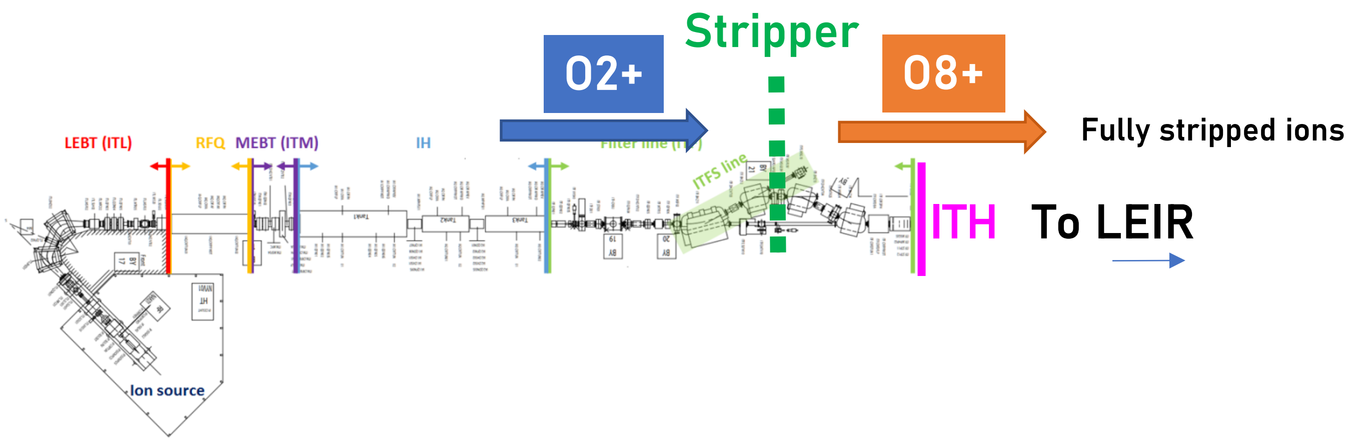




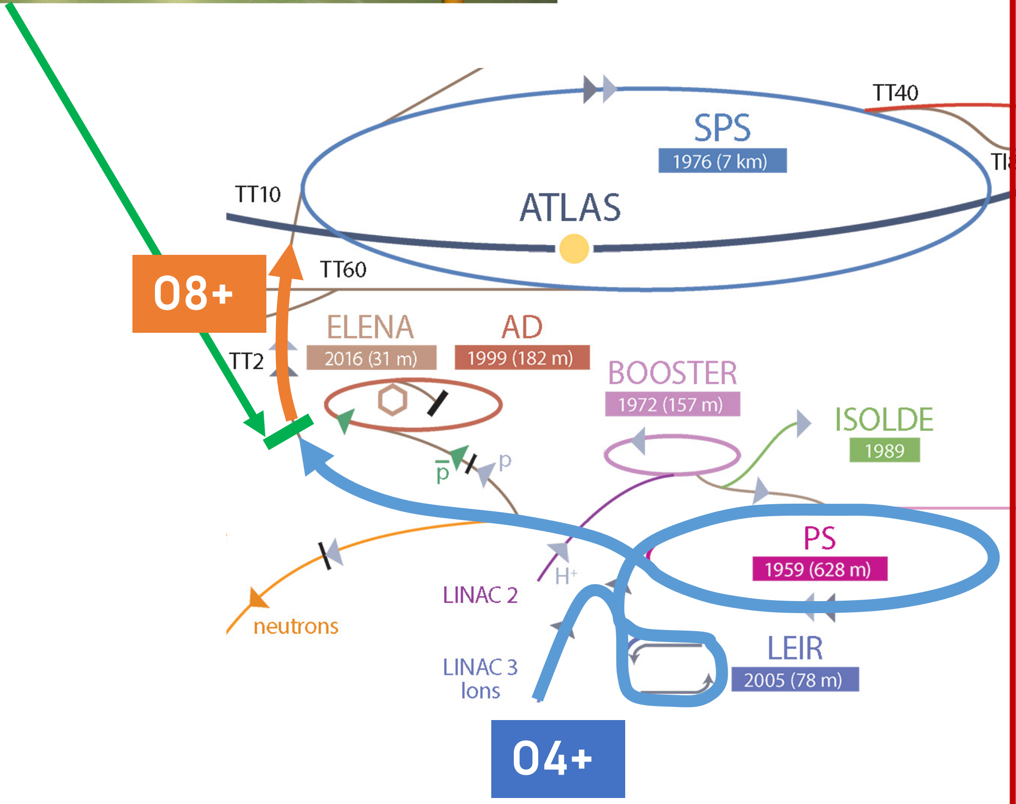
80 m circumference

Charge state options

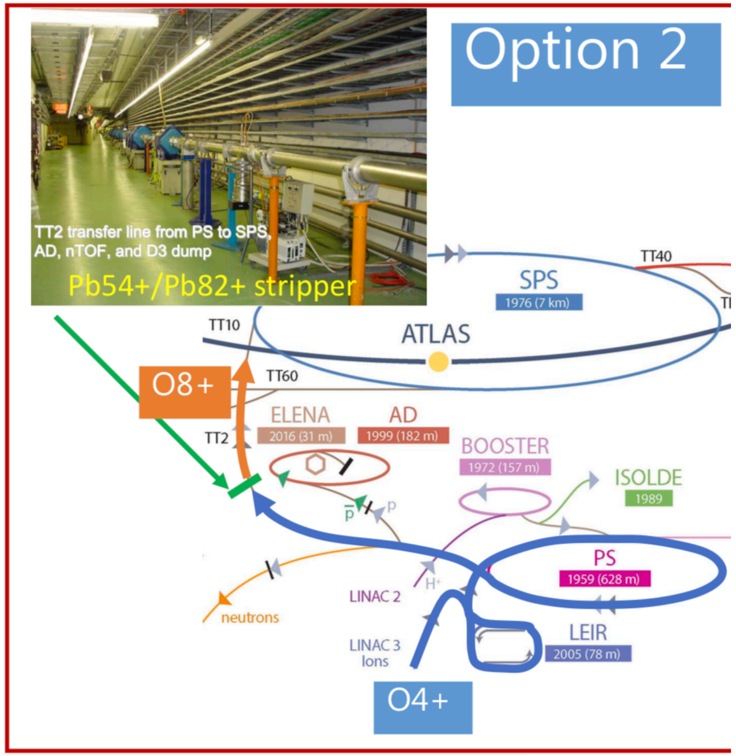
Option 1



Option 2



Beam intensities across the injector chain



Asses bunch intensities → Q=4 (out of L3) & 1 bunch

	Intensity	Comment	Kinetic energy @ extraction (beta)
Ions from **L3** per 200 μs pulse (1e10 ions)	2.2	From measurements (*)	4.2 MeV/nucleon (0.095)
Ions/bunch at **LEIR** injection (1e10 ions)	1.1	Assuming 0.5 injection efficiency. LEIR Space charge limit (1e10 ions) = 2.25	67.2 MeV/nucleon (0.361)
Ions/bunch at **PS** injection (1e10 ions)	0.88	LEIR transmission efficiency = 80%	5.63 GeV/nucleon (0.99)
Ions/bunch injected into **SPS** (1e10 ions) (1e10 elementary charges)	1.42 (5.67)	PS transmission efficiency = 90% Transfer line transmission efficiency = 90% TT2 charge stripping ratio = 8/4	225 GeV/nucleon
Intensity/bunch injected into **LHC** (1e10 elementary charges)	3.97	SPS transmission efficiency = 70%	3250 GeV/nucleon

Intensity compatible with LHC luminosity requirements

(*) LEIR COMMISSIONING http://cdsweb.cern.ch/record/972341/files/lhc-project-report-923.pdf
Preliminary Characterization of the O4+ Beam in Linac 3 https://core.ac.uk/download/pdf/44163997.pdf

In 2020 BE/ABP studied the Oxygen space charge across injectors and concluded that injection into SPS of 4 10^{10} charges per bunch might not be possible. Though we will do Oxygen test in SPS to check experimentally the space charge limit, we have a solution: inject two bunches of 2 10^{10} charges, i.e. double splitting in PS.

Overview of what has been done and what remains to be done

- Preliminary feasibility study and ad hoc working group was stablished in 2019
- No show-stoppers were identified

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Operation Group
BEAMS Department

CERN Div./Group or Supplier/Contractor Document No.
BE - OP

2157814
EDMS Document No.

ION Operation
EDMS Project name :

Date:24/05/2019

ION OPERATION

FEASIBILITY STUDY OF AN OXYGEN RUN IN LHC

Abstract

In several occasions, the LHC Heavy Ion community have expressed its interest in measurements with light ions and in particular for an Oxygen run in RUN3 with Oxygen-Oxygen (O-O) collisions and proton-Oxygen (p-O) collisions. A first assessment of the feasibility of such ion run, has been carried out at the beginning of 2019. In the following, we summarized the most important points and at the end, we present a list of issues that will need to be addressed in case the ion run is approved or we are given the authorization to continue with the preparation of such a run in the injector complex.

Oxygen Working Group

HSE/RP: M. Widorski
BE/OP: V. Kain, F. Tecker, J. Wenninger, M. Schaumann R. Alemany-Fernandez
BE/ABP: H. Bartosik, R. Bruce, M. A. Jebramcik, J. Jowett, D. Kuchler, R. Scrivens
EP: F. Moortgat, B. Pedersen

LHC Machine Committee (LMC)
R. Alemany

Overview of what has been done and what remains to be done

- 27 tasks were identified to be done between 2019 and 2023 for the ion run to take place in the injector complex
  - 11 tasks in 2019-2020
    - all done
    - allowed a preliminary budget estimation to be done and was presented in Feb 2020 at the IEFC and reported to the MTP
  - 6 tasks to be done in 2021
    - **25-29 of May 2021 LN3 Oxygen test**:
      - asses the radiological impact in LN3 with experimental measurements to reduce the theoretical uncertainties
      - according to the results, re-evaluate the risk and mitigations
      - finally, re-evaluate budget for LN3 fencing, beam stoppers and access system interlock
  - 5 tasks to be done in 2022 and another 5 in 2023

Schedule proposal

- Start up ion complex up to PS with Pb
- Week 20 switch to Oxygen
- Week 22 beam to LEIR
- Week 23 beam to PS
- Week 24 beam to SPS
- Week 26 beam to LHC
- Week 27 Pb back to the complex

- 6 weeks of Oxygen commissioning
- 1 week of LHC pilot run

Very ambitious schedule

RADIOLOGICAL IMPACT

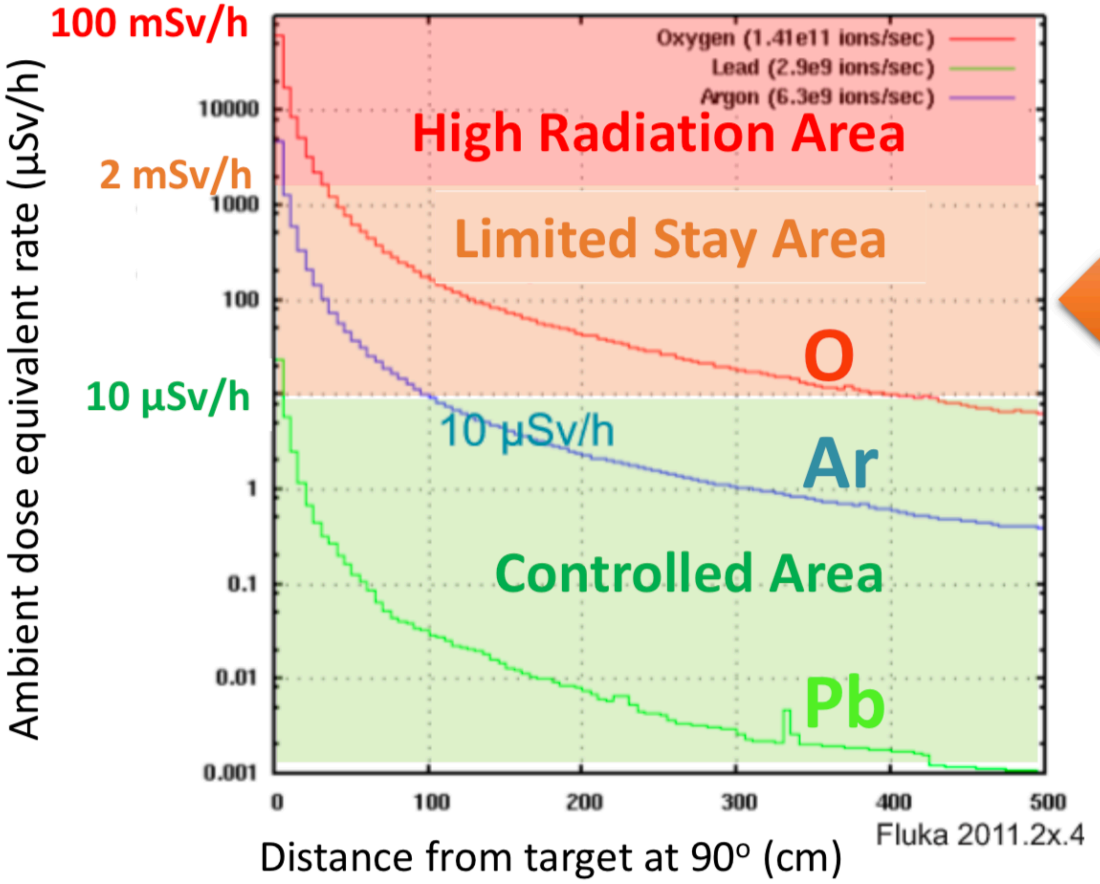
Preliminary simulations have been done concerning the radiological impact of Oxygen beams in the complex since the neutron production is much more important than for Pb.

Due to the uncertainty in the simulations, we need to asses the impact experimentally

25-29 of May 2021 LN3 Oxygen test

Radiological impact in Linac3

	Loss scenario at maximum energy
Linac3	Sustained beam loss inside Linac3 Hall at I_{max}
LEIR	Accidental but sustained beam loss at I_{max}
	Continuous losses at 10% of I_{max}
PS	Accidental but sustained beam loss at I_{max}
	Continuous losses at 10% of I_{max}
	Continuous localised beam loss at stripping



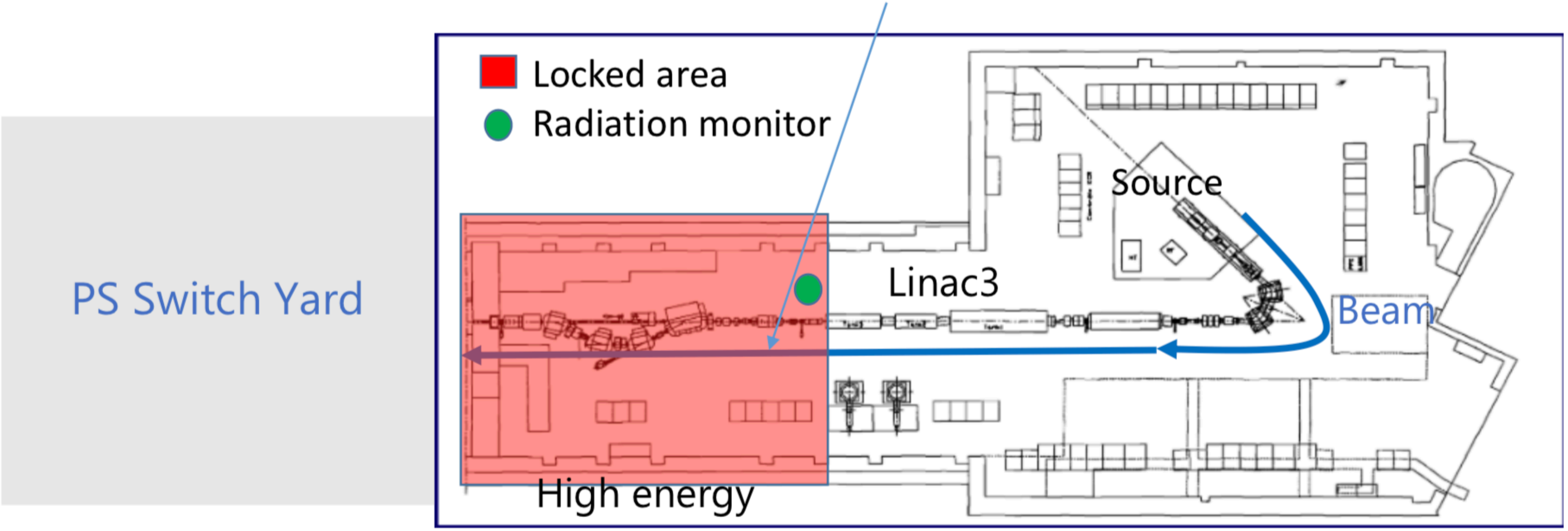
We are here (within uncertainties)

All ions compared for maximum intensities @4.2 MeV/n

Oxygen (1.41e11 ions/sec)
Lead (2.9e9 ions/sec)
Argon (6.3e9 ions/sec)

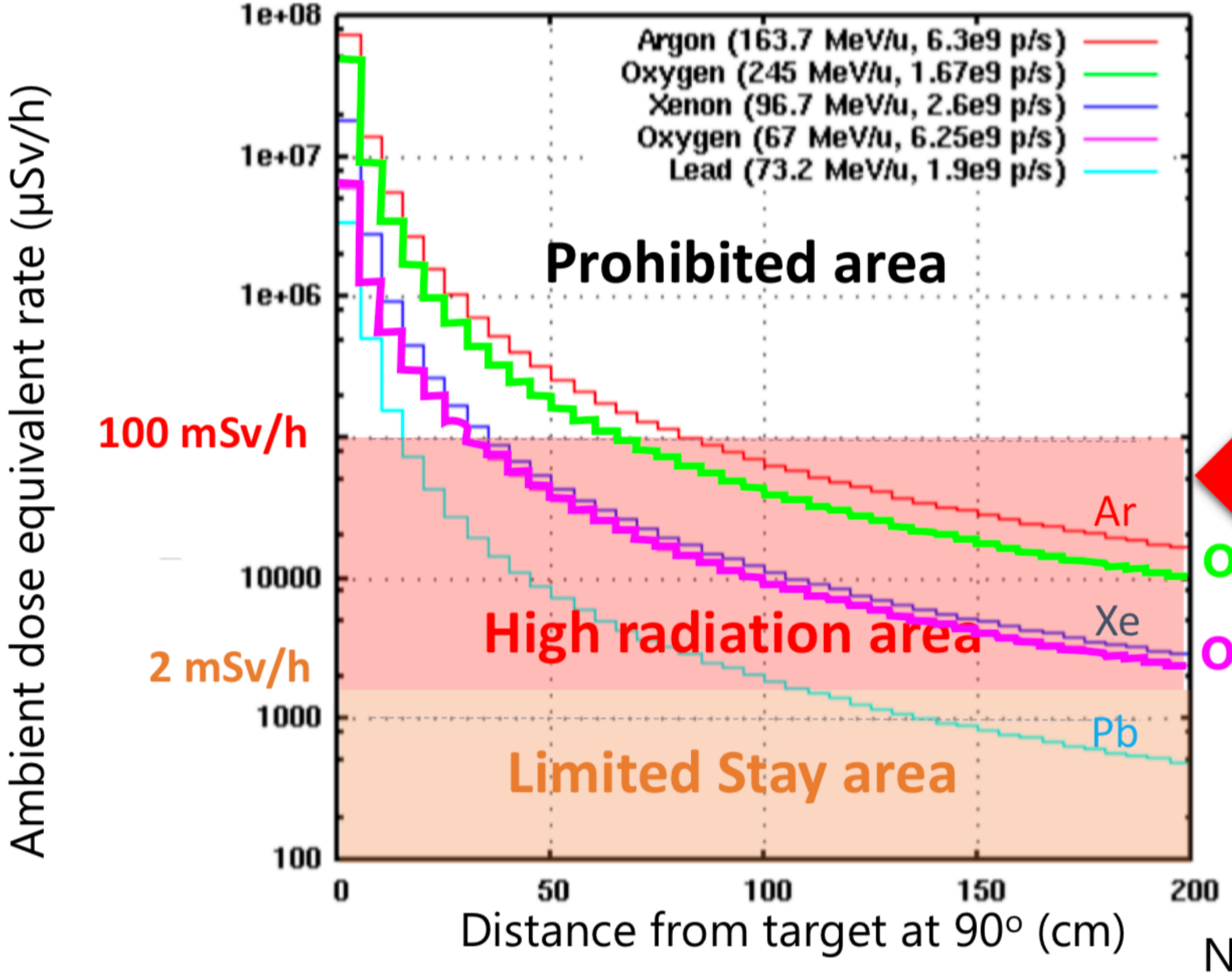
Radiological impact in Linac3

Mitigation action: Creation of a Linac3 high energy beam zone with appropriate barriers and accessibility control. However, some equipment still locked inside.
→ Exact fencing solution to be determined after measurements in 2021



Radiological impact in LEIR

All ions compared for maximum intensities at top energy



Max. energy ➔ determining factor

O8+ at 245 MeV/u is the limiting case, requiring potentially mitigation measures (roof installation ?)

We are here (within uncertainties)

O8+ 245 MeV/u

O4+ 67 MeV/u feasible without additional roof shielding/closure.

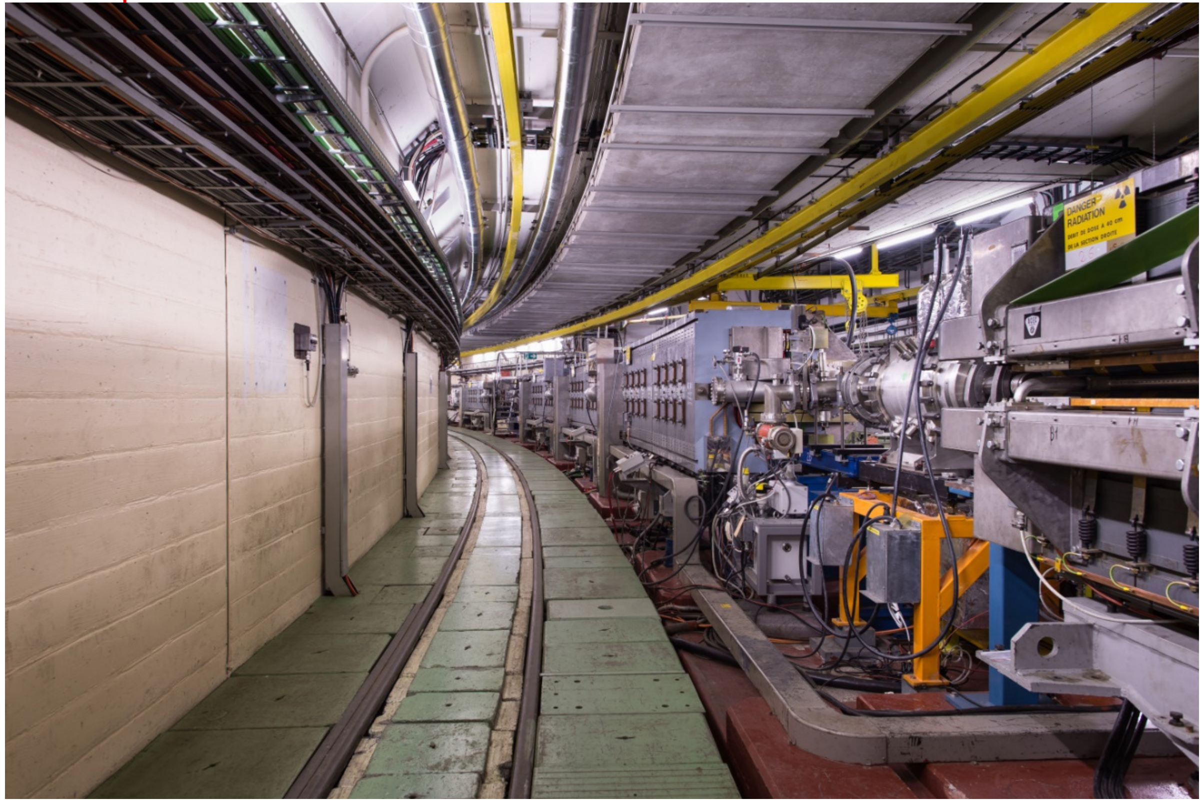
Note: Ar run in 2014 ➔80.7 MeV/u and nominal 1.25E9 ions/s (closer to Xe and O4+)

Radiological impact in PS

	Loss scenario at maximum energy	
Linac3	Sustained beam loss inside Linac3 Hall at I_{max}	
LEIR	Accidental but sustained beam loss at I_{max}	
	Continuous losses at 10% of I_{max}	
PS	Accidental but sustained beam loss at I_{max}	1
	Continuous losses at 10% of I_{max}	2
	Continuous localised beam loss at stripping	3

Constraints:

1. Access chicane between PS Booster and PS (scenario 1, 2)
   Mitigation: PS Booster to be made inaccessible during ion operation



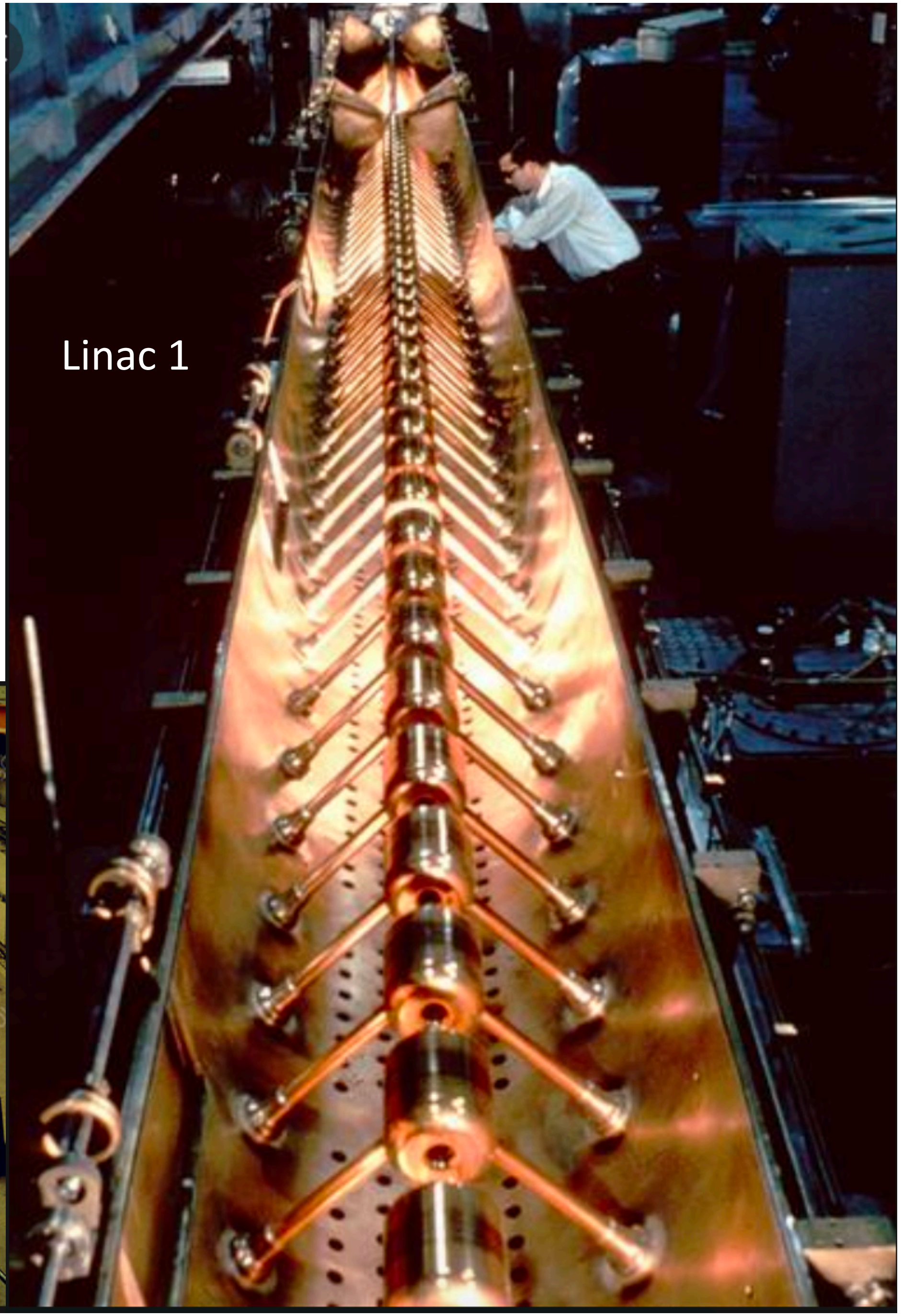
1. **PS switchyard** access system to be interlocked with Linac 3 beam **stopper in ITF** "for oxygen operation only": in case of access in PS Switchyard, the beam will be stopped in ITF, i.e. inside the L3 hall.
2. **Booster** access system to be interlocked with a beam **stopper in ITH** (just before the magnet LT.BHZ30) "for oxygen operation only": in case of access in Booster this will prevent the beam going straight to the Booster, but allowed the beam to go to LEIR.
3. Potential activation at stripping foil (scenario 3) to be studied, no relevant impact expected

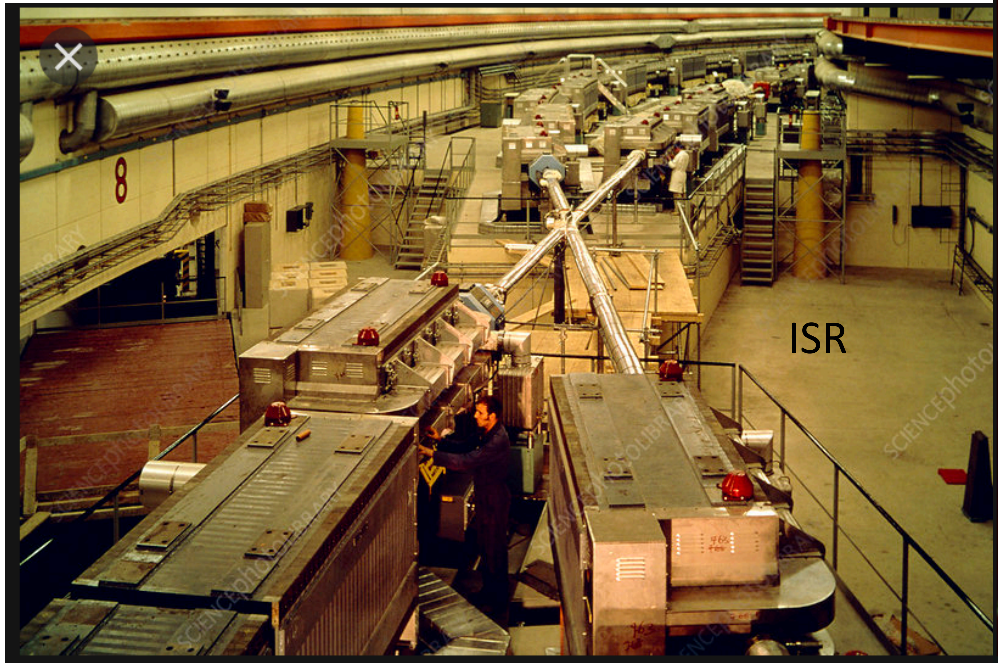
CONCLUSIONS

- The study has been very well organized and conducted with limited resources
- Important conclusions were firmly achieved such we do not have to repeat the feasibility study again if the preparation of the run is postponed for some years
- Thoroughly documented in slides and minutes of each meeting
- Though the study was put on hold from budget allocation point of view, we went on working on the identified tasks that don't need budget or additional resources
  - Space charge simulations (BE/ABP)
  - Simplification of the safety logic for Booster and PS (BE/ICS) ➔ substantial budget reduction
  - Oxygen beam tests May 2021 (BE/ABP & HSE/RP)
- However, all the activities requiring budget (e.g. integration studies) were cancelled
- The "project" resources were addressed pre-covid, i.e. pre-delays. If we resume the project, first we need to re-asses the availability of the groups to continue.

1964

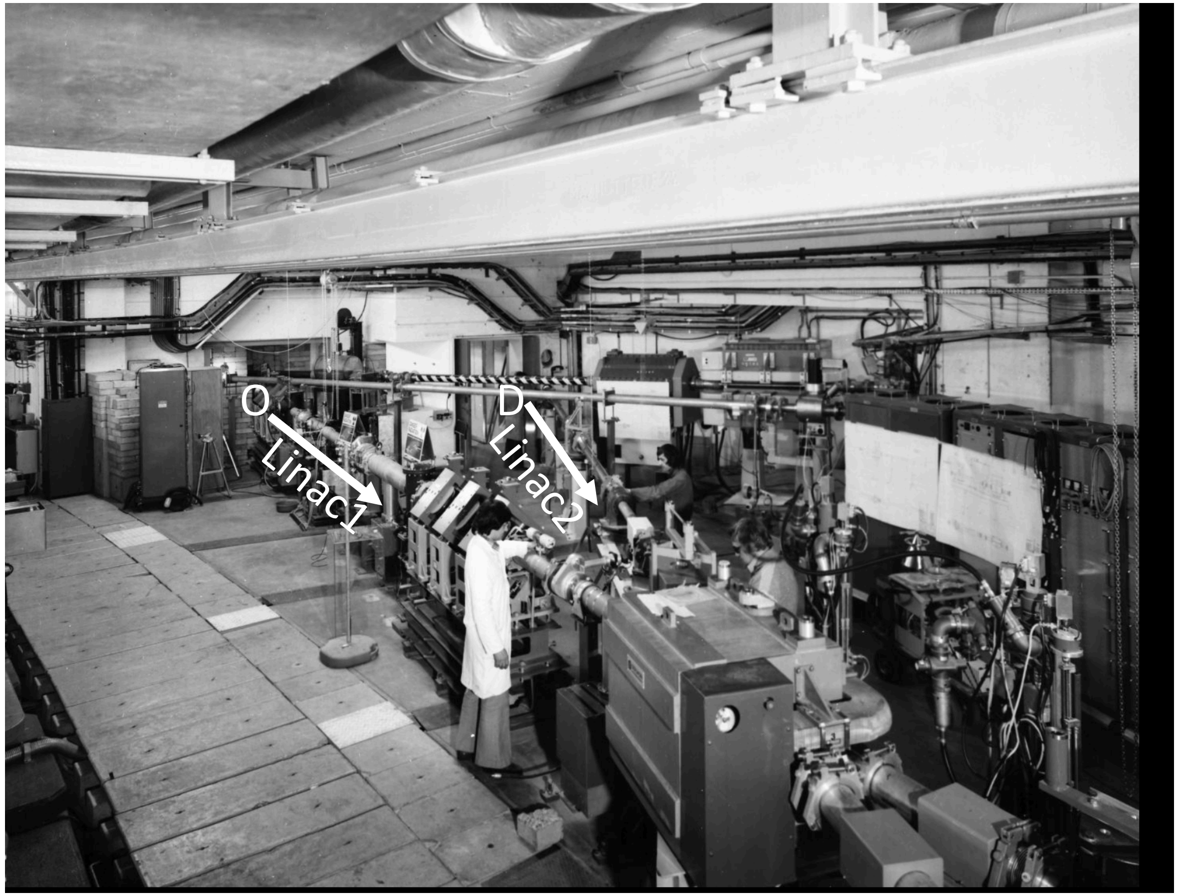
- First machine experiments to accelerate deuterons in Linac 1
- The success of the experiment encouraged the Intersection Storage Ring (ISR) user community to request the first **deuterons** and later on **alpha particles**.
- This development allowed to demonstrate that, without major difficulties, Linac 1 and the downstream machines were able to accelerate **fully stripped ions up to calcium**. A detailed study was, therefore, launched at the beginning of the 80's to accelerate heavier ions than in the past.





1980's

- 1st upgrade of the ion injector complex:
  - Electron Cyclotron Resonance(ECR) source capable of producing oxygen16O6+
  - Radio Frequency Quadrupole (RFQ)
  - 33% increase of the Linac1 RF accelerating and focusing fields
- PS complex was able to alternate operation between **oxygen** ions from Linac1 and **deuterons** from Linac2



- In 1987: new 14 GHz Geller source ➔ higher oxygen intensities + large amount of sulphur 32S12
- Converted to 32S16+ after the stripping foil at the end of Linac1
- PS accelerated **16O8+** and **32S16+** up to transition energy and was then able to continue selectively with the sulphur beam

- The ion complex reached its limits at this point

1990's

- Start a collaboration between different laboratories and CERN to build the first CERN **Heavy Ion** Facility, also called the Lead-Ion Accelerating Facility, to serve the fixed target experiments community ➔ Linac3 was born

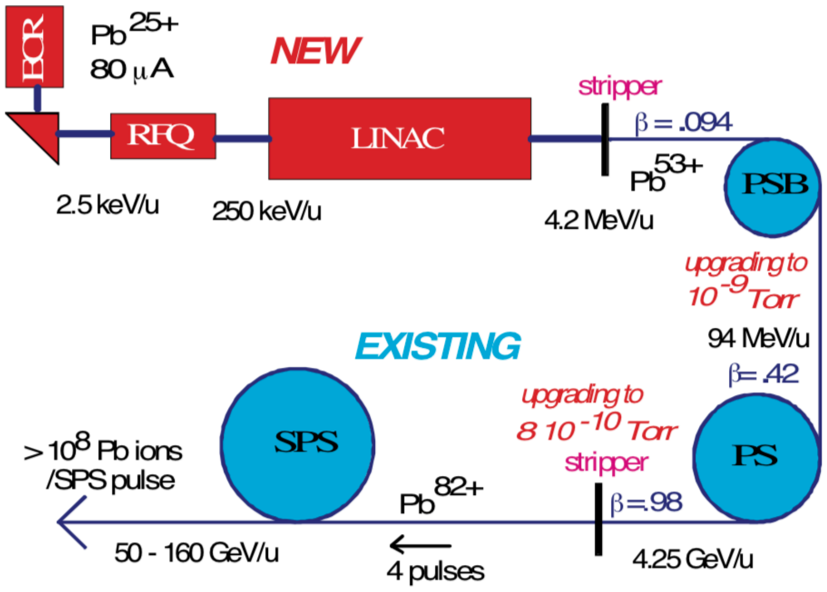
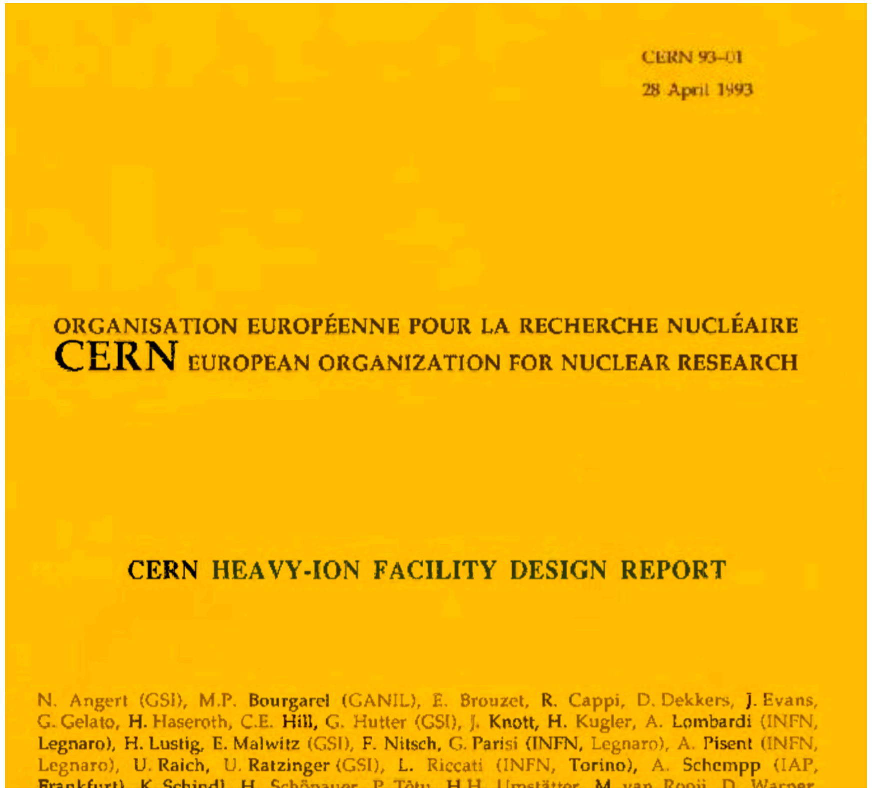


Fig. 1: Layout of the CERN Heavy Ion Accelerating Facility



CERN 93-01
28 April 1993

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN HEAVY-ION FACILITY DESIGN REPORT

N. Angert (GSI), M.P. Bourgarel (GANIL), E. Brouzet, R. Cappi, D. Dekkers, J. Evans, G. Gelato, H. Haseroth, C.E. Hill, G. Hutter (GSI), J. Knott, H. Kugler, A. Lombardi (INFN, Legnaro), H. Lustig, E. Malwitz (GSI), F. Nitsch, G. Parisi (INFN, Legnaro), A. Pisent (INFN, Legnaro), U. Raich, U. Ratzinger (GSI), L. Riccati (INFN, Torino), A. Schempp (IAP,

First physics runs in 1994

- The new ion complex unable to satisfy the LHC luminosity requirements by three orders of magnitud

1993

- In December 1993 the first LHC ion program was proposed to the CERN Council as part of the Large Hadron Collider, LHC Project Proposal.
- 1996 ➔ LHC Conceptual Design Report

➔lead ion collisions with a centre-of-mass energy per nucleon of 5.52 TeV/n ➔7 Z TeV beam energy, and a luminosity of $1.95 \cdot 10^{27} cm^{-2} s^{-1}$

- Low Energy Ion Ring (LEIR) was born from the conversion in situ of the Low Energy Antiproton Ring (LEAR)