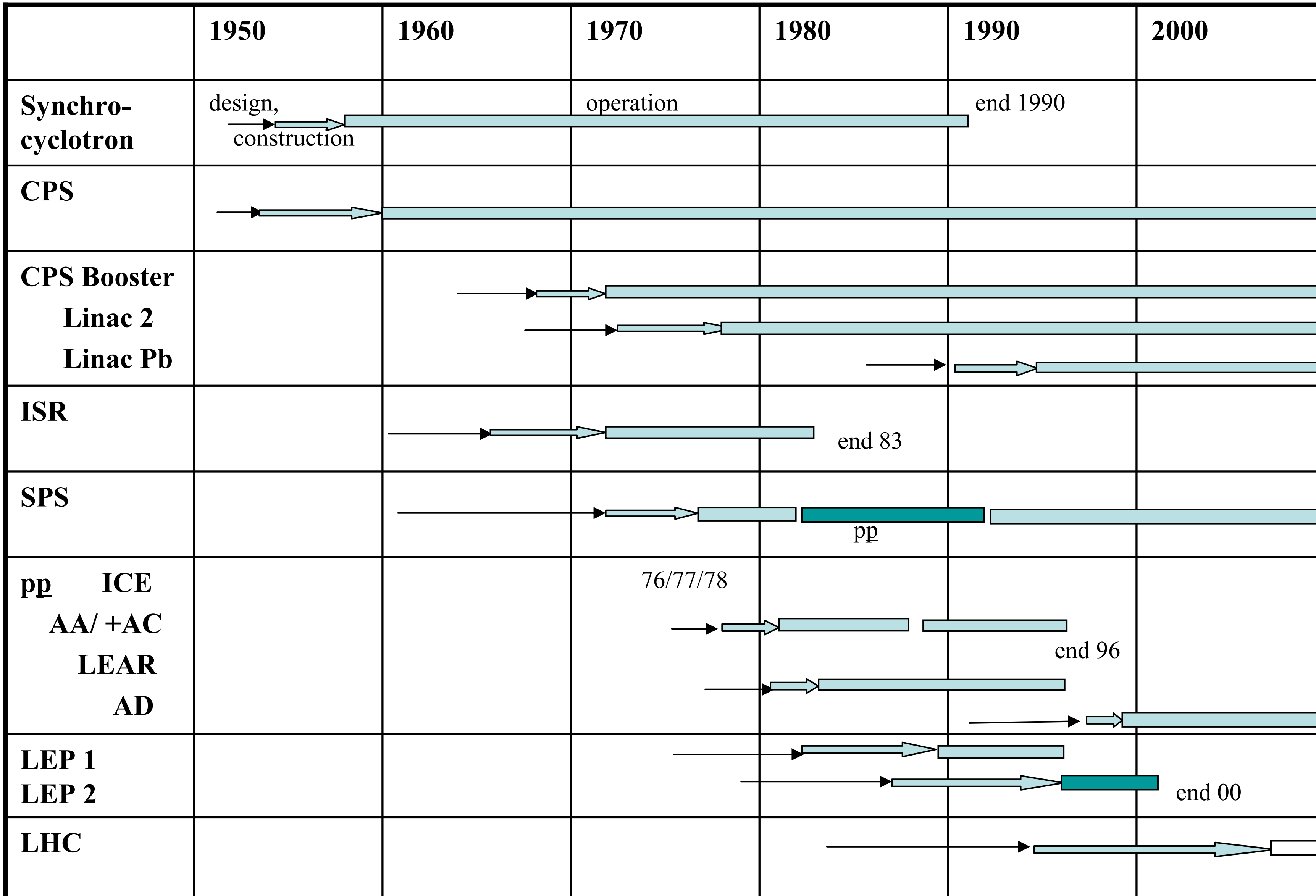
Accelerators at CERN

- Early times (SC, PS, PS improvement)
- Expansion into France (ISR, SPS)
- Next steps (antiprotons, LEP, LHC)
- Future options for CERN
- What we learnt

This lecture is dedicated to **Mervyn Hine**, distinguished accelerator physicist and man of vision, who made eminent contributions to the build-up of the accelerator complex at CERN. He passed away in April 2004.

Evolution of Accelerator Park



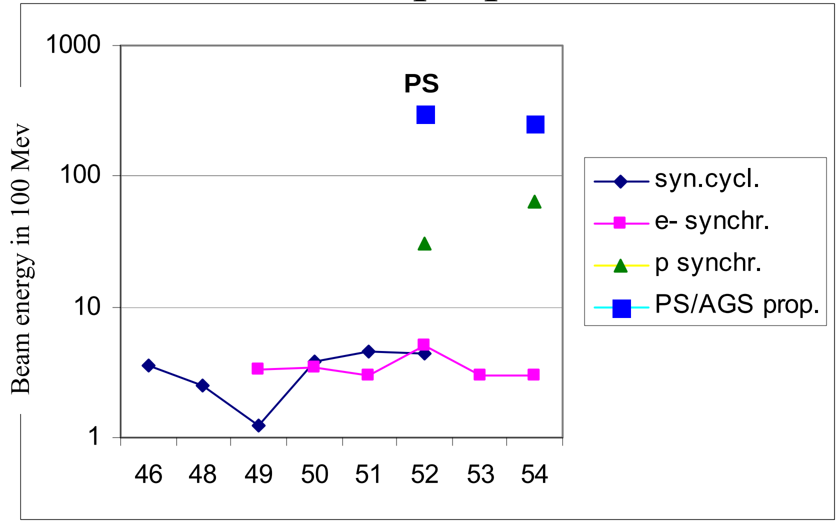
The Starting Conditions at CERN

- 1st Meeting of Provisional **CERN Council May 1952** >> Creation of Study Groups:
  - -- Synchro-cyclotron (Cornelis Bakker, Amsterdam)
  - -- "Cosmotron 3>>10-20 GeV" (Odd Dahl, Bergen) visited BNL in August 1952 and learned about new principle for focusing: Alternating-Gradient (AG)
- **Council October 1952** decided on their proposal
  - -- abandon scaled-up weak-focusing "Cosmotron">> go for 30 GeV PS based on AG for ≈ same cost.
- **Subsequent work** >> balancing of
  - -- size of vacuum chamber and magnets, i.e. cost
  - -- sensitivity to B-field inhomogeneity and alignment errors

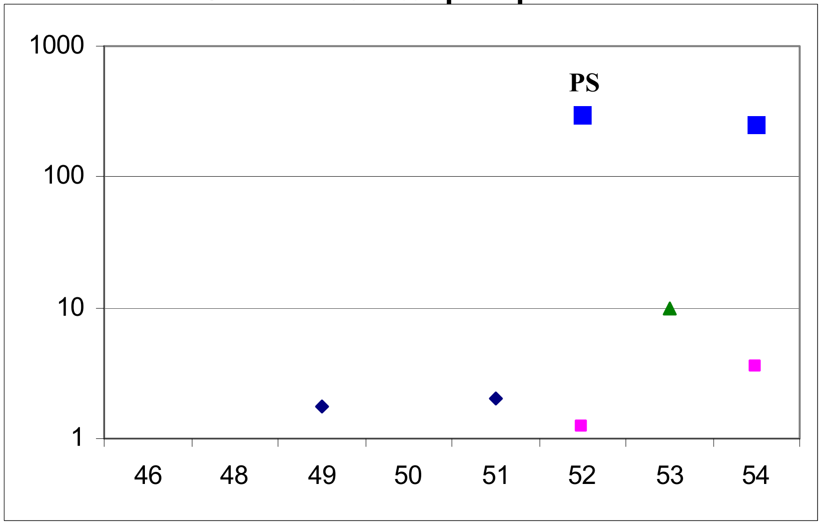
e.g Weight of magnets (t): 800 (53/1), 10000(53/4),3300(54/3), 3800(now)

The Starting Conditions: International Context

cf. US and CPS proposal



cf. EU and CPS proposal



Choice of new focusing principle >> bold step >>

"For awful gamble stands AG but if it works or not we'll see (R.Peierls)

>> result: **CERN starts level with US and ahead of other EU**

Others did not trust AG: US: ZGS/ANL; UK: Nimrod/RAL; JINR: S.P.tron

CERN 600 MeV Synchro-cyclotron

- **Provisional Council October 1952: decided to go ahead in ‖ with CPS for**

  -- early start of meson physics

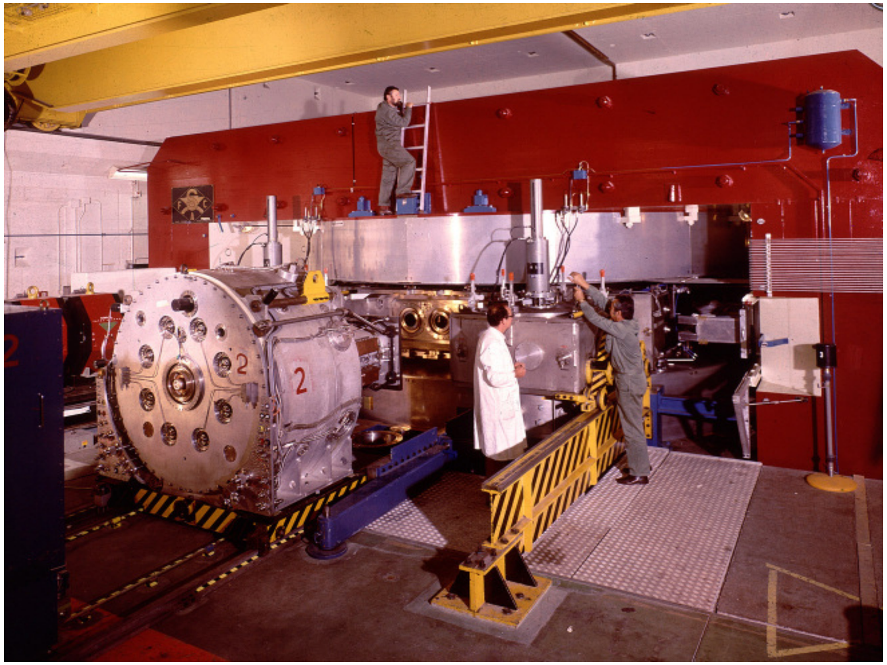
  -- training for accelerator technology
- **Construction : 1955 >> First beam: 1957 (immediately at max. energy)**
- **ISOLDE: 1964 shift HEP >> NP**
- **Stop: end of 1990**

  ISOLDE moved to CPS Booster (PSB)

  Machine (radio-active) still in Bld. 300 !

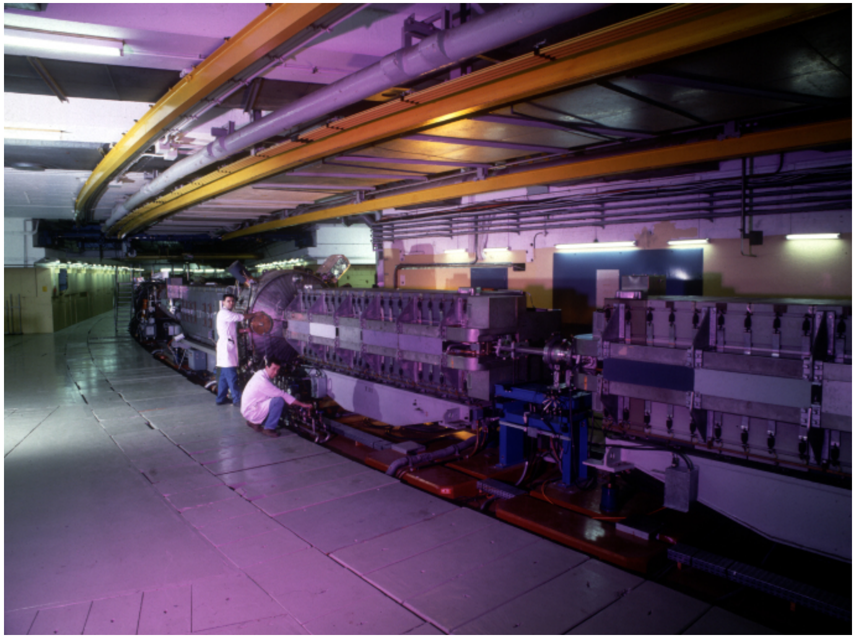
Comment: its progress was reassuring for Council and good physics was done

but tied physics community in the 50's >> disservice to PS experimental programme (which started only 1961 about 2 years after PS start-up)



CERN 26 GeV Proton Synchrotron (CPS)

- Oct. 53: first PS group to GE
- May 1954: ground breaking
- Design: AG combined function
  (dipole + quad), 2π R = 628 m
- Dec. 1959: first beam to 28 GeV
- Drama: no beam line equipment,
  rudimentary detectors



- Learnt : beam physics with AG,
  producing precise magnets
  precise alignment
  rf control
  management of large project

Improvement Programme for CPS

- **Extraction of proton beam**

Fast: many or all bunches in 1 turn
ν-horn 61,mov. kicker 63, FAK 69,
Slow: spill over many turns (1963)

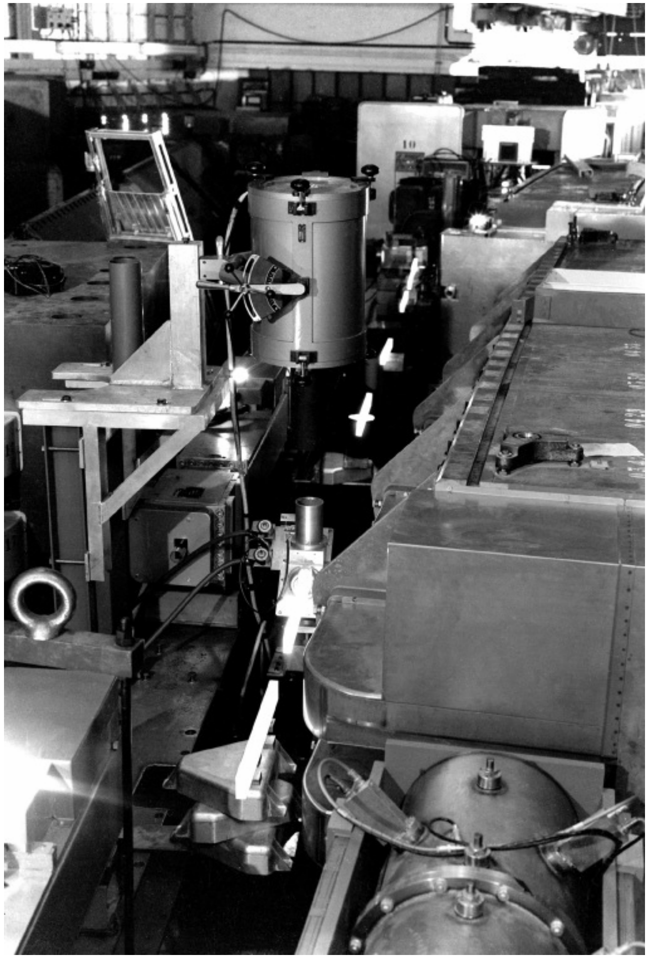
- **Increase of average current**

-**New power supply and rf** for CPS
for 2x repetition rate
-New injector: N_{Spch} at PS inj. ~ $\beta\gamma^2$
4-ring 800 MeV booster synchrotron
inserted:L1/PSB (Constr.68-72) /CPS
- **Linac 2 + new p-source**
Constr.73-78, replacing Linac 1 ↓

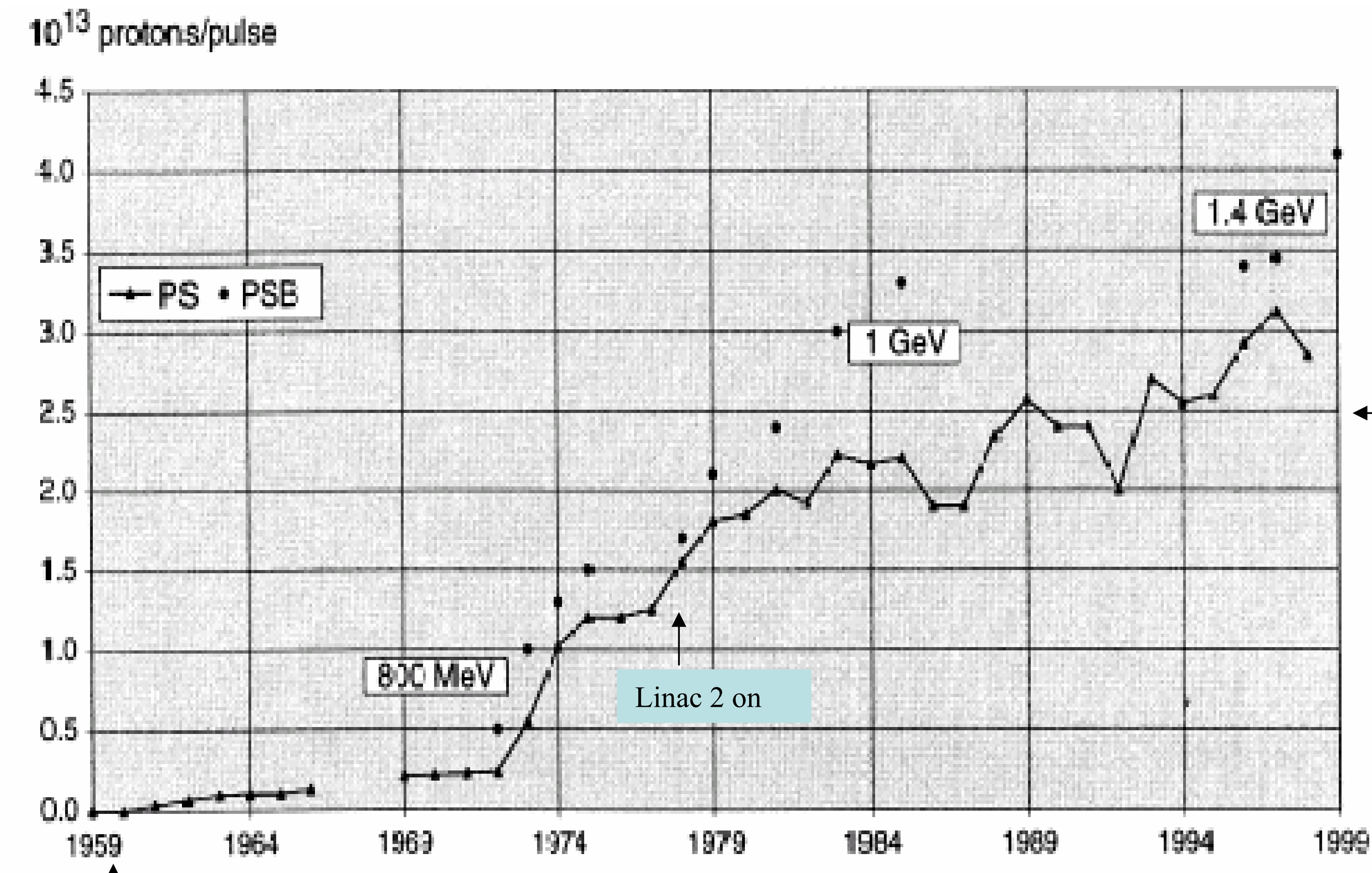
- **Ion programme :** L1 (d,α, O, S);

New Pb linac: Constr. 90-94 by coll.

Fast extracted beam 25 GeV



Evolution of CPS and PSB Intensity



Linac 2 on

final PS average for WA ν providing 2×10^{13} p/s (design: $5\text{-}8 \times 10^{9}$ p/s)

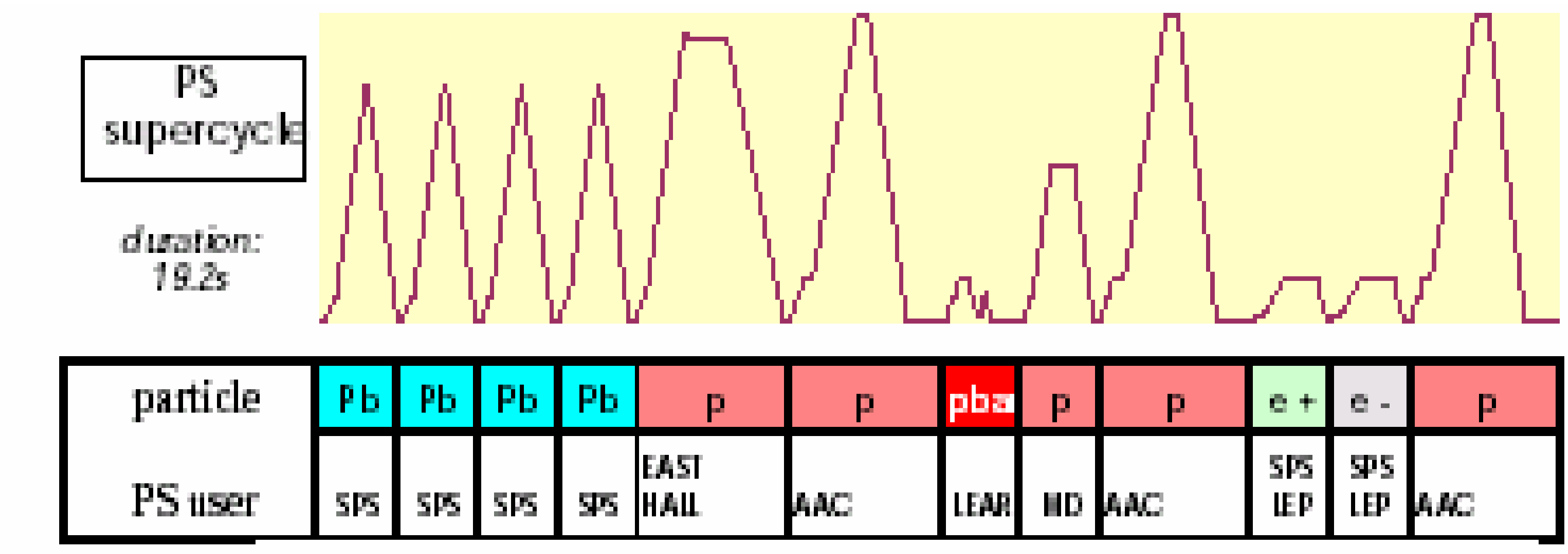
2.2×10^{11} in mid 60

$\approx 1 \times 10^{10}$ design

PS Complex Improvement

Learnt: - to deal with high intensity beams and ions up to Pb

- low-loss fast and slow CPS ejection (internal targets removed in 1980)
- merge bunches by using more than one rf system for $\underline{p}$ production
- refined computer control allowing for flexibility in supercycles



D.J.Simon EPAC 96

Intersecting Storage Rings (ISR)
“The Leap in the Hadron Collider Area”

pp collider up to 31.4 GeV /beam
2π R = 942 m, injection from CPS
Combined-function lattice, large $\Delta p/p$
8 Intersection points (5 used for exp.)
Constr.: 66-70, Operated:71-83

L= 4 x 10^{30} (des.) to 1.4 x 10^{32} $cm^{-2}s^{-1}$,
dc proton current: up to 40 A (57A)
Notable features:
- Ultra-high vacuum and ion clearing
- Low-impedance vacuum envelope
- High-stability of power supplies (10^{-7} ripple tolerance on dipoles)
- Superconducting low-β insertion (L increased by 6.5)

but experiments not fully exploiting it.

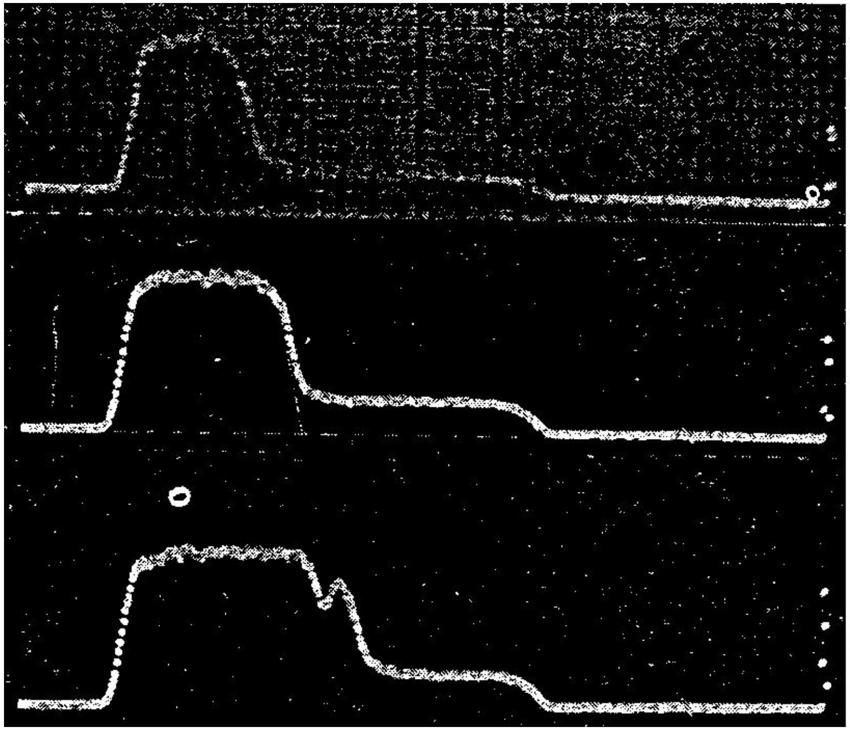
View of intersection point 5 in 1974

Selected ISR Achievements

Non-destructive beam diagnostics of coasting beams with Schottky noise

For monitoring particle distribution

- <p>, Δp, density f(p) ⟶
- extrema of betatron tunes in stack,
  rms amplitude and tune
  at particular orbit
  by measuring fast and slow wave signals (n +- Q) f_{rev}



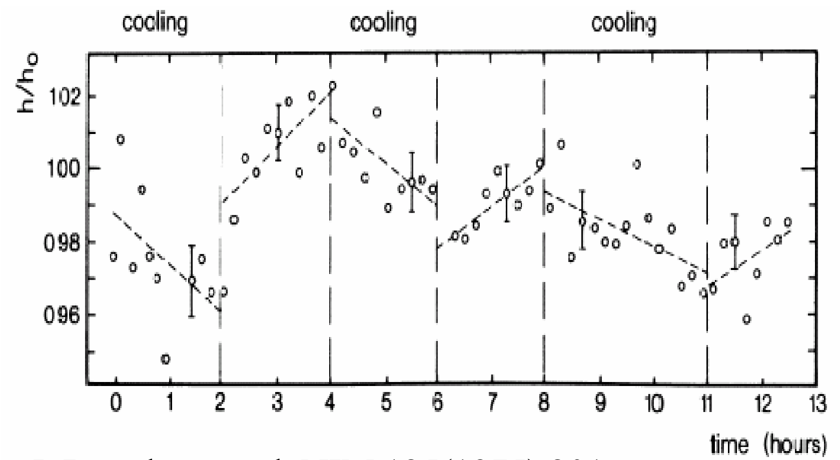
Example: Longitudinal Schottky scan
$(dN/dp)^{1/2} = f(p)$
at 10, 15, 19 A proton current

J.Borer et al., HEACC (1974) 53

Selected ISR Achievements

Resurrection of stochastic cooling and experimental test (theory: van der Meer 1968)

Measurement of relative effective beam height with cooling on and off

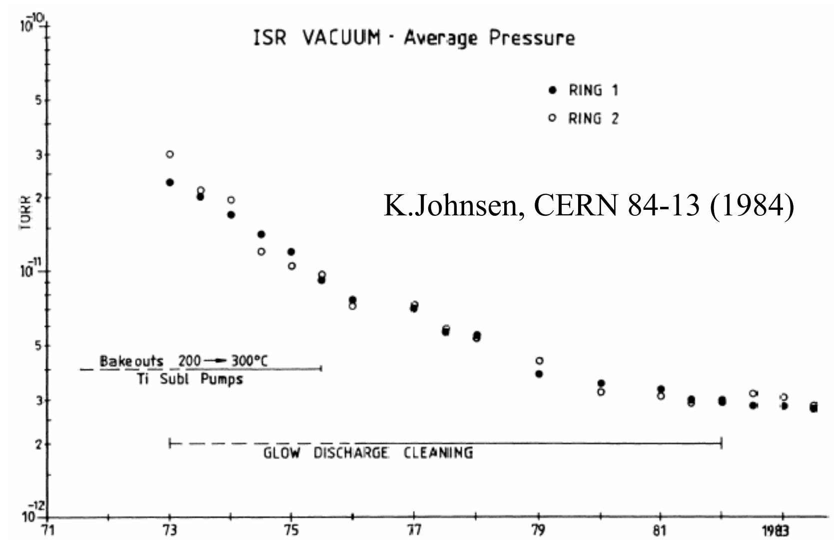


P.Bramham et al. NIM 125(1975) 201

Use in ISR: e.g. $\underline{p}$ beam kept for 345h

Ultra-high vacuum technology

Evolution of average pressure: design nTorr, at end pTorr



K.Johnsen, CERN 84-13 (1984)

Fig 5 The average pressure of the ISR vacuum for the years 1971-83

Result: physics runs up to 60 h, beam lifetime of about 3 to 4 months

Super Proton Synchrotron (SPS)

Concept: 300 GeV in early 60's
Site: final Prevessin 1970 > use PS
Construction: 1971- 1976
E= 450 GeV p, 158 GeV/u Pb (1986)
N(p)= 4.5 x 10^{13} /cycle (4.5 x design)

We learnt:
- deep tunneling (Δ= 2 cm / 1.2km)
- direct powering from grid with reactive power compensation*)
- rf acceleration with TW structure
- computer control from start*)
- start experiments with accelerator

Separated function, classical magnets
$2\pi R$ = 6912 m (11 x PS),
2 big exper.halls (West, North)

Neutrino beam to Gran Sasso (730km) under construction, operation 2006 →
LEP and LHC injector

*) at smaller scale already at PS Booster

Search for the step after ISR/SPS

Investigated in 74 – 78:

CHEEP: 27GeV e- ↔270 GeV p in SPS with new e- ring in SPS

LSR/SISR : 400 GeV pp collider

MISR: 60 GeV p storage ring (ISR magnets) ↔ SPS

SCISR: 120 GeV sc p rings in ISR

US: FNAL pp study (stop 78)

ISABELLE pp constr.78-83 (stop)

Winners: (Decision/First collisions)

i) pp in SPS (1978 / 1981)

medium-term: “quick and dirty”

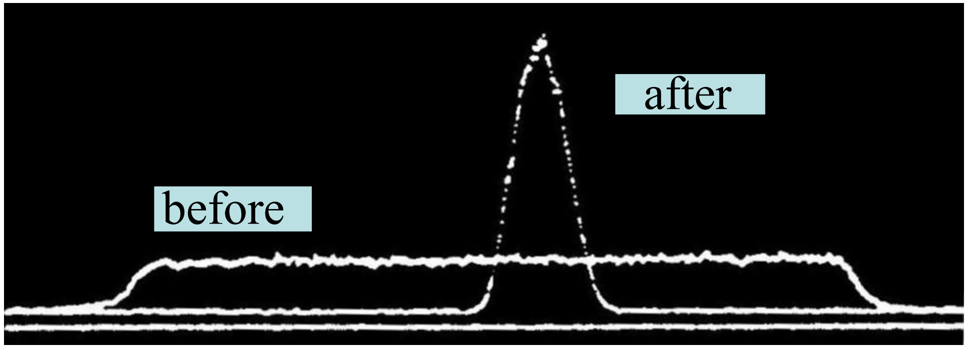
ii) e+e- in LEP (1981/ 1989)

long-term: “flagship”

ICE test ring demonstrated 1978

- stochastic cooling in longitudinal phase space, simultaneous cooling in all 3 dimensions
- lower limit τ (p) > 32 h ≡ O(9) up!

Example of p-distribution in ICE before/after stochastic cooling dN/dp = f (p)



CERN Annual Report 1978

The $p\underline{p}$ Programme

- **Antiproton Accumulator (AA)**

3.5 GeV/c storage ring, $2\pi R$= 157m

Built 79-80 (AA), stochastic cooling

- **New beam transport lines**
- **SPS Modifications:**

Vacuum: 200 nTorr (des.)>> 2 nTorr

Low-β insertions for UA1 and UA2

RF modifications (TW,add 100 MHz)

Electrostatic deflectors for separating the 6 bunches/beam in 9 points

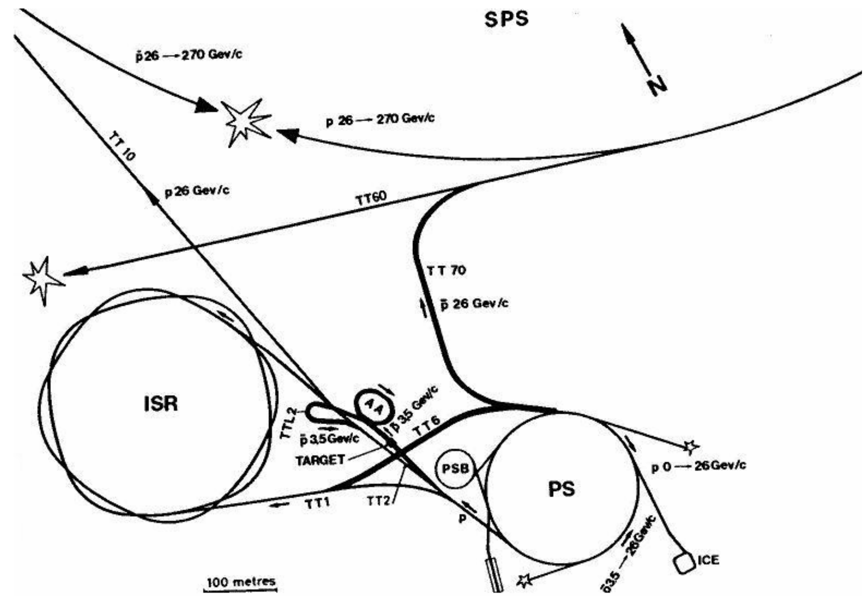
- **Antiproton Collector (AC) +**

3.5 GeV/c storage ring, $2\pi R$=182m,

Added in 86, operational in 1987

for 3D precooling,stack cooled in AA

>> Overall gain of ≈ 6 in $d\underline{N}/dt$



Accelerator layout
(new elements >> in bold)

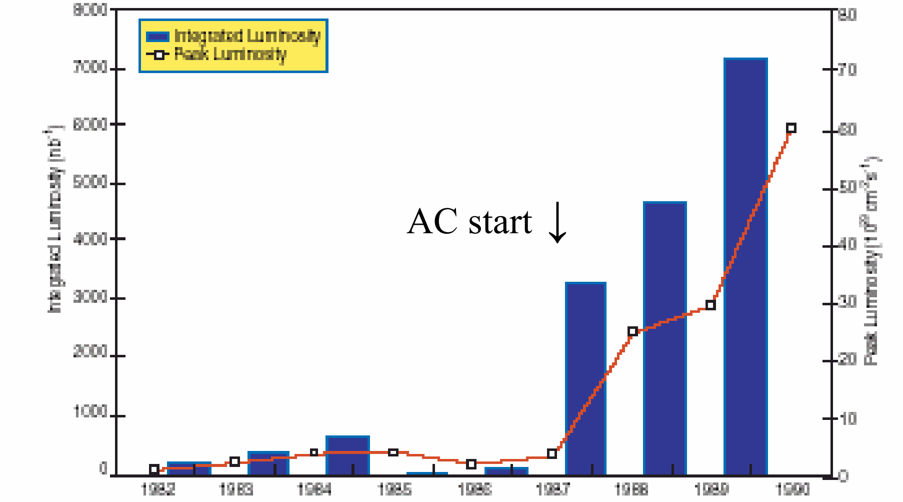
-AA+AC peak performance:

$d(\underline{p}) \uparrow = 4 \times 10^9$, $d\underline{N}/dt = 10^{12}$ $\underline{p}$/d

≈ two fills of SPS/d (T_{coast}=10h)

>> little reserve >> cliff-hanging !

pp Performance SPS



G.Brianti, Eur.Phys.J.C 34 (2004) 15

Energy (GeV): 273 (82-85)/315(87-91)

Operation: risk of loss of stack (1d of p prod.!) or of beam during acceleration

Learnt: b-b effect with bunched beams
Intra-beam scattering in bunches
Large 4π detectors

Antiproton Programme

- **LEAR** p buffer ring and decelerator in PS South Hall

Built: 80-82; Operation: 82-96
T= 1.2 GeV to 5 MeV

Ultra-slow ejection: spill for <10 h
Stochastic and electron cooling

- **Antiproton Decelerator (AD)**

modif.AC: p buffer and decelerator
Built: 98-00; Operation: 00 →
T = 2.7 GeV to 5.3 MeV
Stochastic and electron cooling

Extracted beam is further decelerated in RFQD down to T= 120-10 keV

Large Electron Positron Ring (LEP)

Design : 1975 – 1981 with iterations

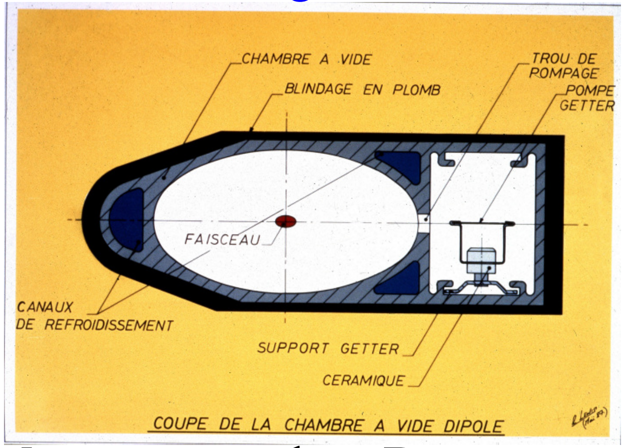
	1977	1978	1979	**1984**
E (GeV)	100	70	86	**55**
2πR (km)	52	22	31	**27**
Experim.	8	8	8	**4**
P_{rf} (MW)	109	74	96	**16**

Choice of site: PS/SPS as injector

Construction: 1982 – 1989

Operation: 89-95 (Z_0), 95-00(> Z_0), 1997 W-threshold

Technical challenges: **Vacuum**:



Dipole magnets: low B > concrete-steel magnets (steel filling 27%) > B reproducible, cheap and rigid

RF system: 350 MHz Cu cavities 1.5 MV/m, storage cavities for $P_{rf}\downarrow$ by 1.4; 1 MW tubes. LEP 1 (Z_0): V_{rf} = 0.4 GV

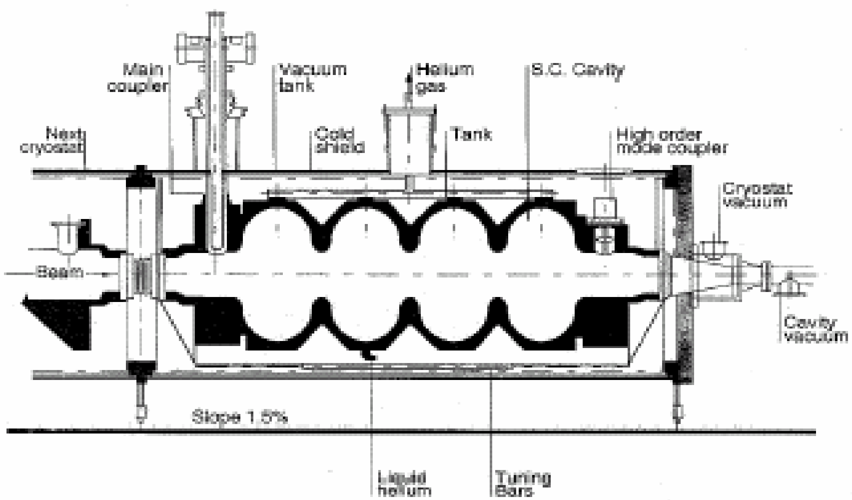
Upgrading to LEP 2

For $V_{rf} \sim \gamma^4$ >> massive increase for reaching W-pairs and beyond required:

- **Superconducting (sc) cavities**: start study in 79, 20 Nb bulk cavities ordered 89, then switch to Nb-film

  Operated at 350 MHz and 4.5 K;

  Successful transfer of technology developed at CERN to industry



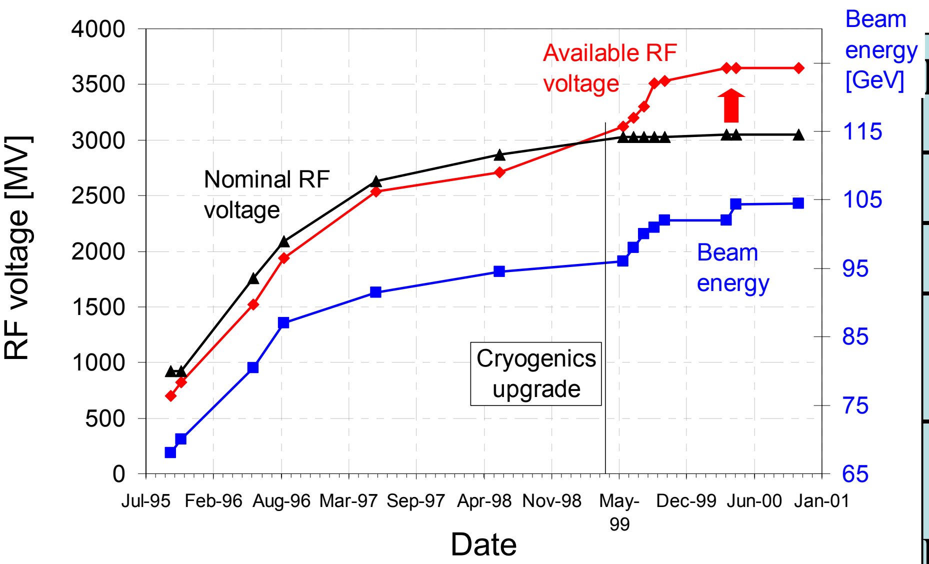
- **rf power**: 2 new rf galleries + tubes
- **Cryogenic system** : transfer lines and refrigerators 4 x (6 → 12 kW)
- **beam focusing**: 10 sc quads for the four low beta insertions

Final rf configuration:

272 Nb-film cav. 7.5 MV/m
nominal 6 MV/m
16 Nb cav. 4.5 MV/m
56 Cu cav. 1 MV/m
490 m sc active length
43 Klystrons
V_{rf} = 3.6 GV total voltage (sc+Cu)

LEP Achievements

R.W.Assmann, Chamonix (2001)



Performance: E_{max} = 104.5 GeV

206 pb^{-1} at Z_0

784 pb^{-1} at or above W-threshold

from 12 pb^{-1} (90) >> 254 pb^{-1} (99)

Potential: +94 sc.cav >> 111 GeV

Learnt to master:

- large scale excavation (tunnel/halls)
- large scale sc rf and cryo-system
- operation with strong syn.rad and radiation damping of beams
- precise beam energy calibration: error for M_w = 10 MeV by beam

Learnt to deal with perturbations by:

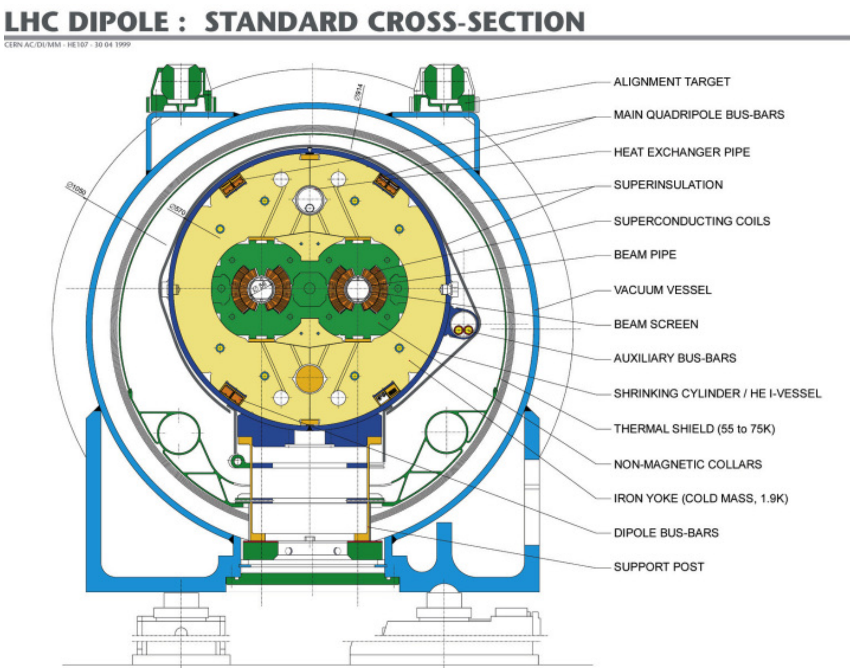
- earth currents by F-trains (1.5 kV, dc) >> $\Delta B/B \approx 2 \times 10^{-4}$ / 12h
- earth tides/rain changing $2\pi R$ by ≈ 1mm ≡ 10 MeV in beam energy
- beer bottles in the vacuum chamber

Large Hadron Collider (LHC)

Parameters:
Proton beam energy: 7 TeV
L = 1.0 x 10^{34} cm^{-2} s^{-1}
Pb ion beam energy : 2.8 TeV/u
L = 1.0 x 10^{27} cm^{-2} s^{-1}
Installed in LEP tunnel

Chronology:
Design: 83 – 94
(considered since mid 70's)
Approval:
- 94 (two-stages 5 → 7TeV)
- 96 (single stage 7 TeV) with substantial NMS contributions

Operation: 2007 →



Dipole magnet: B = 8.3 T, 12 kA,
Nb-Ti sc 6-7µm filaments > cables,
1.9 K He II cooling, Δx = 194 mm b-b
cold mass: L = 16.5 m overall, 28 t

LHC Challenges

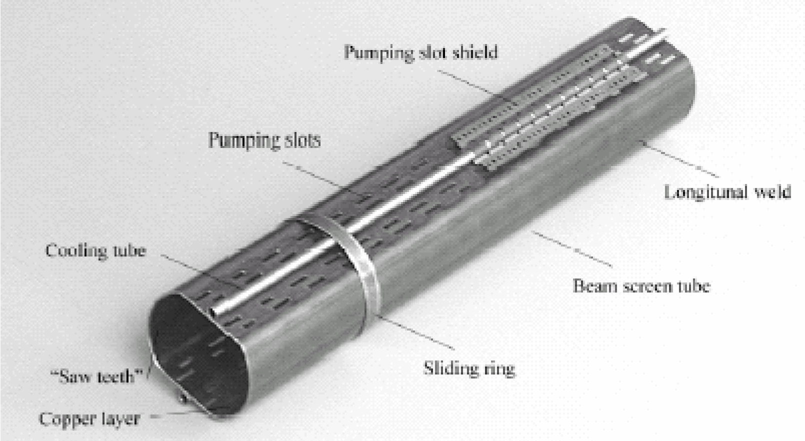
- **Dipoles** : (similar problems for quads)
cable production,
quench protection W_{em}=7 MJ + low T > low heat capacity of cable ,
strong forces (2MN/m per coil quadrant)

- **Cryogenics**:
upgrade 4.5 > 1.9 K LEP refrigerators,
plants and cryo-lines for superfluid He,
deal with quenches > rapid cool-down

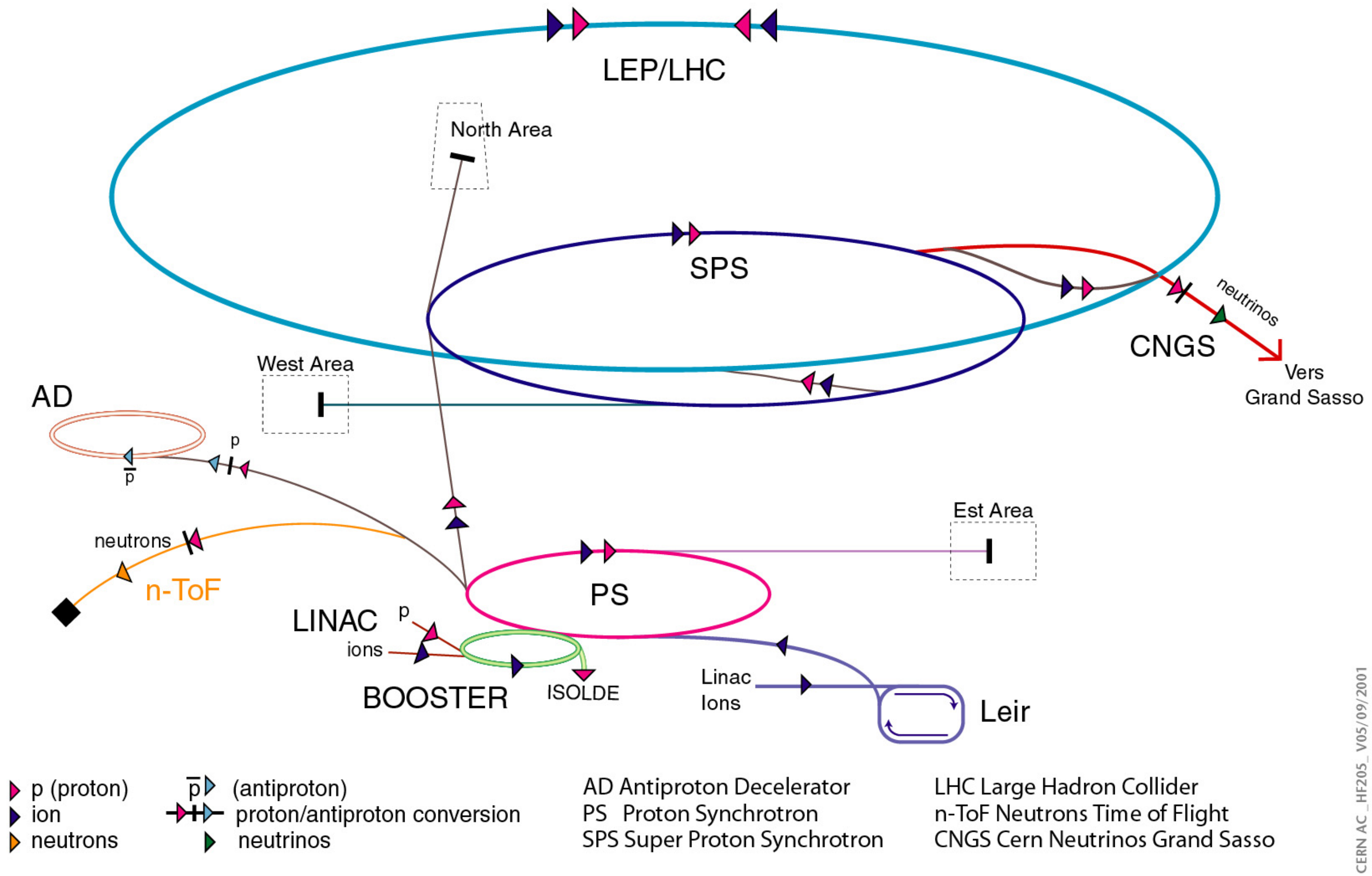
- **Vacuum**: for 100 h beam lifetime >
good pumping by 1.9 K cold tube > protected from syn.rad 0.2 W/m by
beam screen →

- **Collimation and beam dumping**

- **Beam dynamics:**
b-b effects in IP and 120 parasitic crossings near IP (2808 bunches)
electron-cloud effects: 25 ns bunch spacing + beam-induced multi-pactor > dense e-clouds >
i) heat load on beam screen
ii) beam instabilities
Remedies: sawtooth in chamber, coating, scrubbing with beam.



Accelerator chain of CERN (operating or approved projects)



Accelerator Options after LHC

- **Hadron colliders:**

Upgrade LHC luminosity $10^{34} \rightarrow 10^{35}$

Upgrade LHC energy 14 → 28 TeV ?

VLHC (40/200 TeV phase I/II)

Not here, CERN participates

- **Lepton colliders:**

ILC (0.5 – 0.8/1.0 TeV)

Consensus: the "next" project

Not here? CERN participates?

CLIC (0.5 – 3 (5?) TeV)

future flagship?

μ+μ- collider in TeV class ??

- **Advanced neutrino beams**

Superbeam: ν_μ but not very pure

uses ISR tunnel

Neutrino Factories:

- Based on β decay in ring: ν_e

uses CPS and SPS

- Based on μ decay in ring: $\nu_e \, \underline{\nu}_\mu$

Comment: all have synergies with ISOLDE, EURISOL, and neutron-spallation source;

rather decoupled from LHC/ILC results?

LHC upgrade

For increase of luminosity

$$L = n_b f_{rev} N_b^2 F / (4\pi \sigma^*)$$

act on

- n_b – number of bunches per beam
- N_b – number of protons per bunch
- σ^*- beam size at IP ($\sigma_x = \sigma_y$)
- F – $1/(1+(\theta.\sigma_z/2\sigma^*)^2)^{1/2}$

Staged approach (simplified):

(Details in O.Brünig et al. LHC Project Report 626)

Phase 0: IP layout changes for θ ↑

Collide beams only in IP1,5

Increase N_b to b-b limit

$L = 1 \times 10^{34} \rightarrow 2\text{-}3 \times 10^{34}$

Phase 1: hardware modifications

Increase focusing in IP
($\beta^* = 0.5 \rightarrow 0.25$m)

Increase n_b and further N_b

$L \rightarrow 5\text{-}7 \times 10^{34}$

Requires new insertion quadrupoles

(Nb_3Sn => VLHC technology)

Phase 2: energy increase => major upheaval and vigorous R&D in sc

Change magnets, dipoles 8 →15 T

SPS with sc magnets for E_{inj}= 1TeV

Modify injectors for denser beams

Beam energy: 7 → 12 TeV

Operational: 2020? Worthwhile ??

International Linear Collider (ILC)

E_{cm} = 0.5 to 0.8 (1) TeV

L = 3 to 6 x 10^{34} cm^{-2} s^{-1}

R&D by DESY, KEK, SLAC ….

Recent recommendation by ITRP:

sc Nb accelerating structures:

1.3 GHz, 2K >> 25-35 MV/m >>
33 km overall length

Next step: set up Central Team

Challenges:

Long damping rings: 2 x 17 km

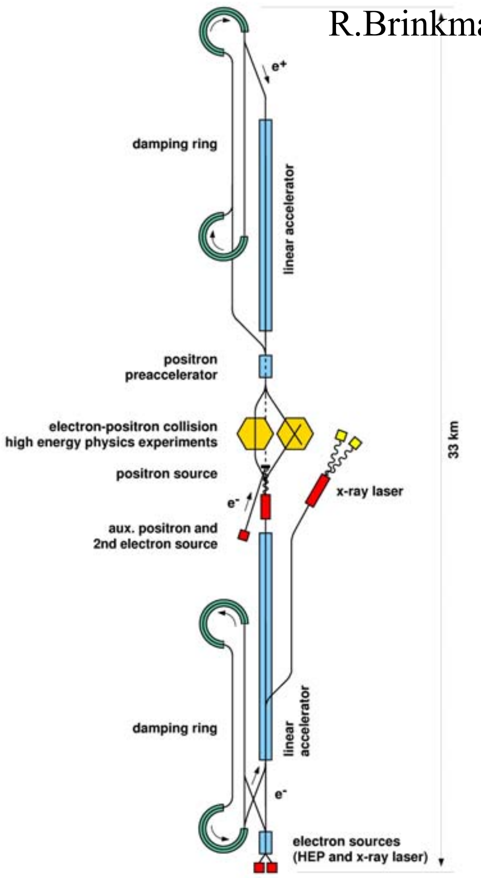
Non-conventional e+ production

Final focus for $\sigma^*_{x,y} \approx$ 400/3 nm

Up to 20 MW beam power

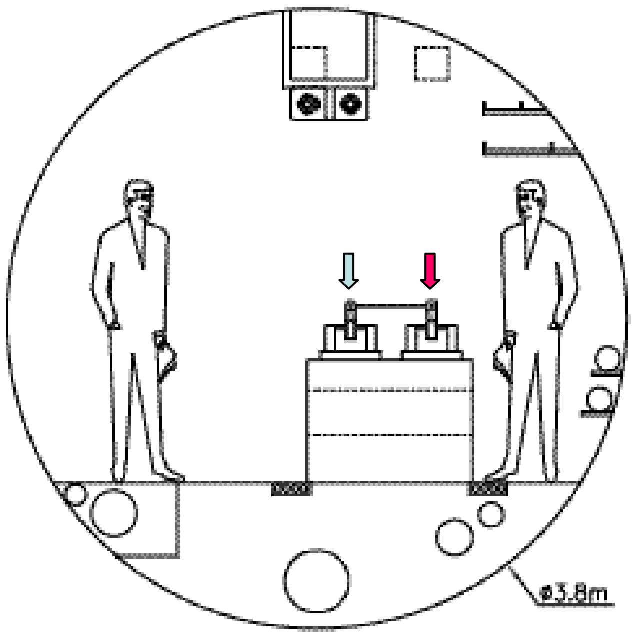
TESLA Layout

R.Brinkmann, HEP03,2003



Compact Linear Collider (CLIC)

CLIC tunnel cross-section



Very compact (30 GHz, 150 MV/m),

Short (0.5/3 TeV => 10/33 km)

Main beam: 0.009 to 1.5 TeV

beam pulse: 1 A pulse in 102 ns

Drive beam: 2 to 0.2 GeV

beam pulse: 150 A in 130 ns

Active R&D by CLIC collaboration to validate concept by the time LHC results available

CLIC challenges:

-- 172/150 MV/m (without/with beam)

-- Generation and control of drive beam

-- Demonstration: needs big unit

Production mechanisms for Neutrino Beams

ν from π and K mesons (EU, JA, US)

$$p \rightarrow \text{target} \rightarrow \pi^+ (K^+) \rightarrow \mu^+ + \nu_\mu \quad \text{process a)}$$

$$\mu^+ \rightarrow e^+ \; \nu_e \; \bar{\nu}_\mu \quad \text{process b)}$$

a) Used at present and medium term (KEK, FNAL, CERN)

b) Proposed for ν-factory based on μ storage rings; **Issues:**

- proton beam power up to 4 MW (p-accelerator, target)
- ionisation cooling of μ beams (test proposed)
- rapid μ acceleration ($c\,\tau_\mu = 658$m)

ν from beta-decay (studied in EU) : e.g.

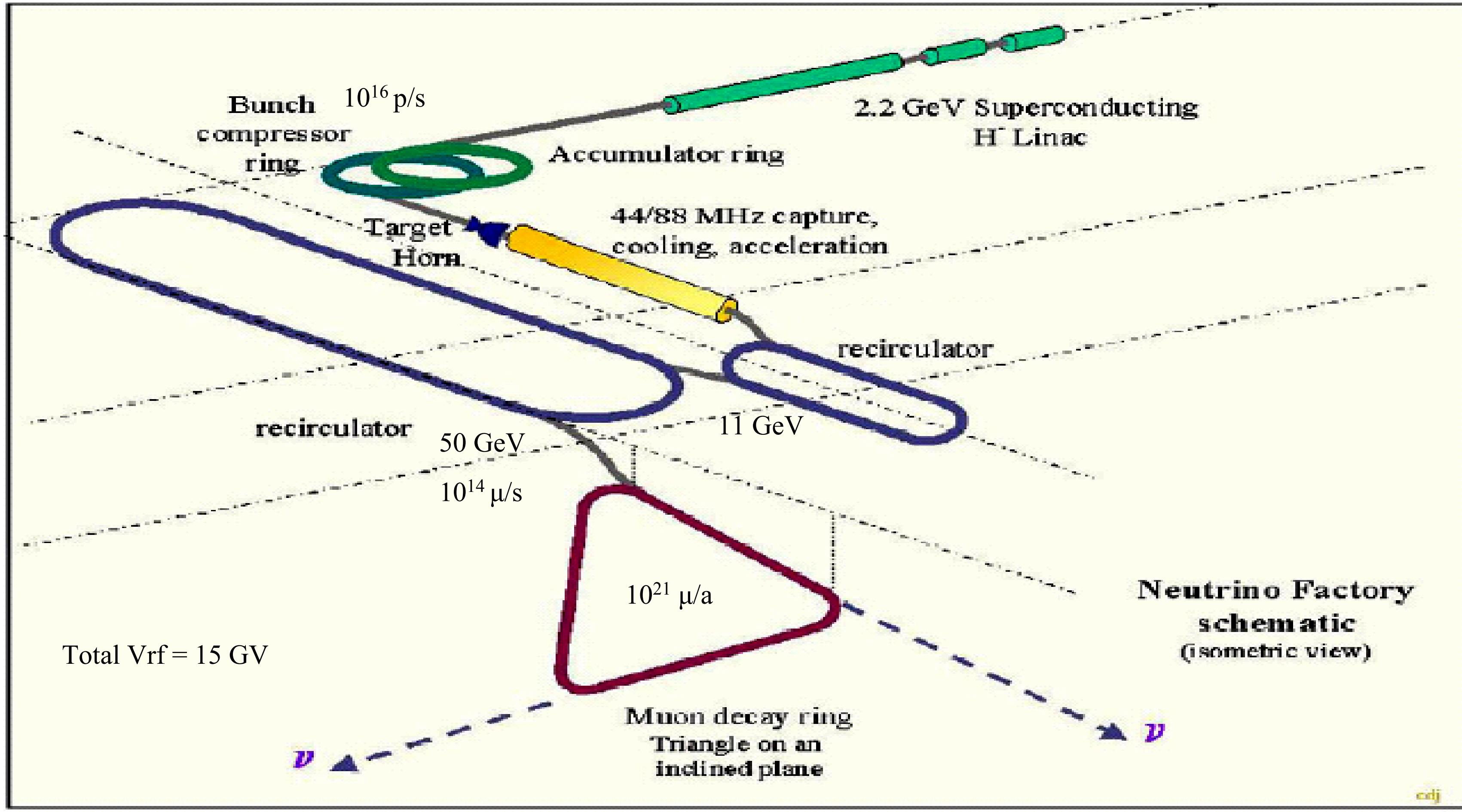
$$^6He^{++} \rightarrow {^6Li^{++}} \; e^- \; \bar{\nu}_e$$

proposed for ν-factory based on storing beta emitters at high energy ($\gamma = 100$) in a storage ring ; **Issues:**

- generation of beta emitters (ISOL technique)
- losses during acceleration (PS,SPS) => contamination

Common issues: handling of hot target & comp., authorisations

Neutrino beam from μ –decay

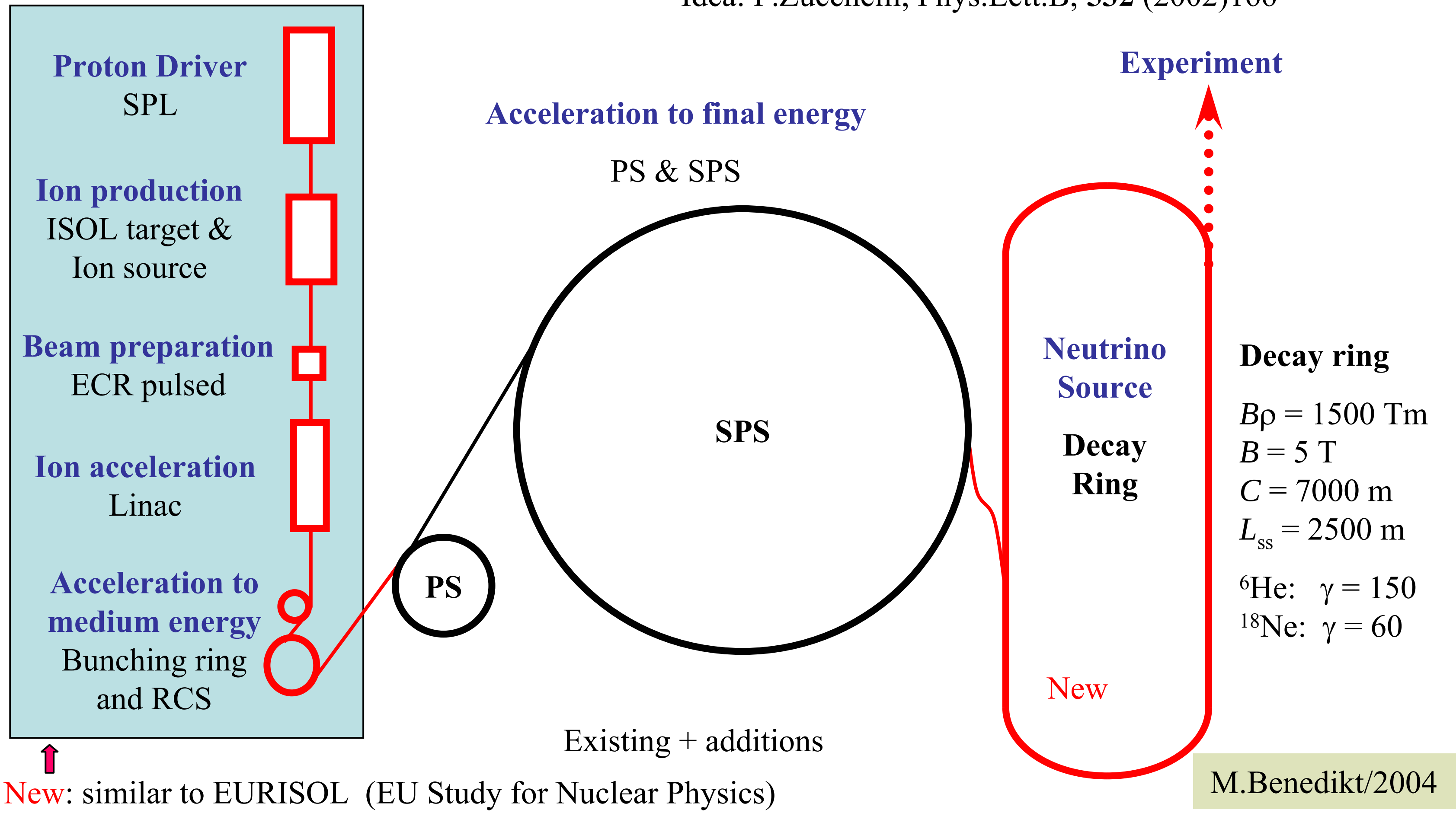


P.Gruber et al., Study of a European Neutrino Factory Complex,CERN/PS/2002-080(PP)

Electron Neutrino beam from β –decay

AIM: provide beams of electron (anti) neutrinos by decay of beta active ions.

Idea: P.Zucchelli, Phys.Lett.B, **532** (2002)166



New: similar to EURISOL (EU Study for Nuclear Physics)

What we learnt

- Projects have very long lead time and will become more global
- Exploit fully existing facilities, also by upgrading or re-use but
- Stop facilities when not leading-edge
- Avoid exaggerated competition leading to rush decisions

- Go for projects, don't fool around with uncommitted R&D
- Work on operation/construction & on future in parallel
- Work in close collaboration with users from inception
- Participate actively in global R&D >> otherwise others choose your future

- Full-scale tests of hardware/ideas whenever possible
- Master the technology yourself before order to industry
- Young staff >> biggest asset of CERN >> teach them and work with them