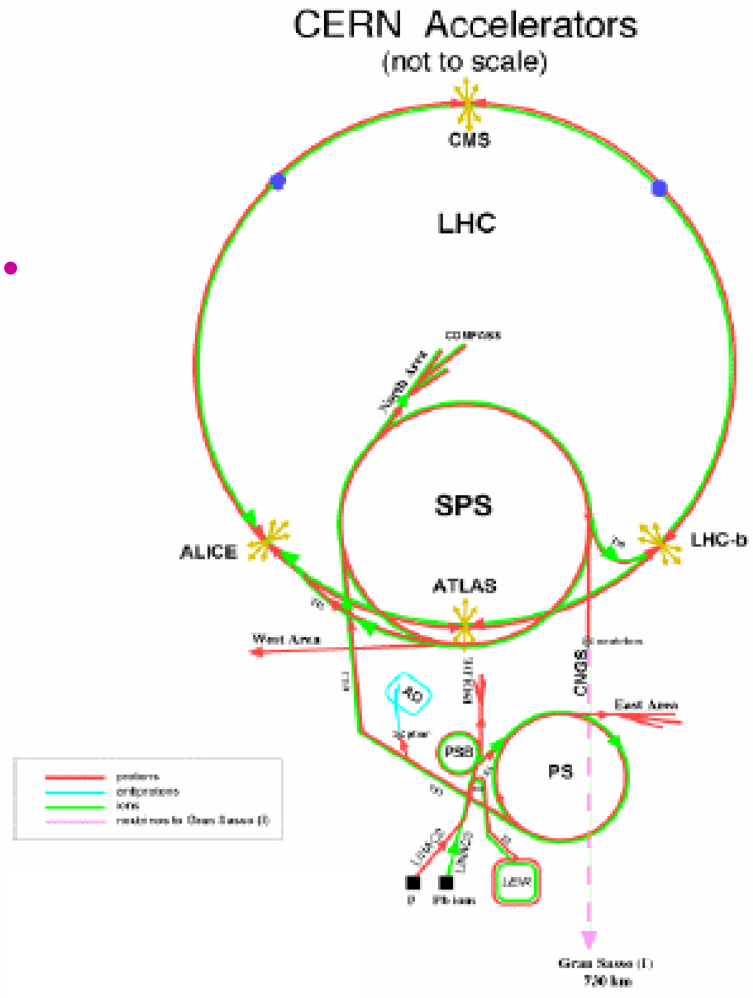
A Walk through the LHC Injector Chain….

Part 3: Ions



Karlheinz Schindl AB/ABP

Contents

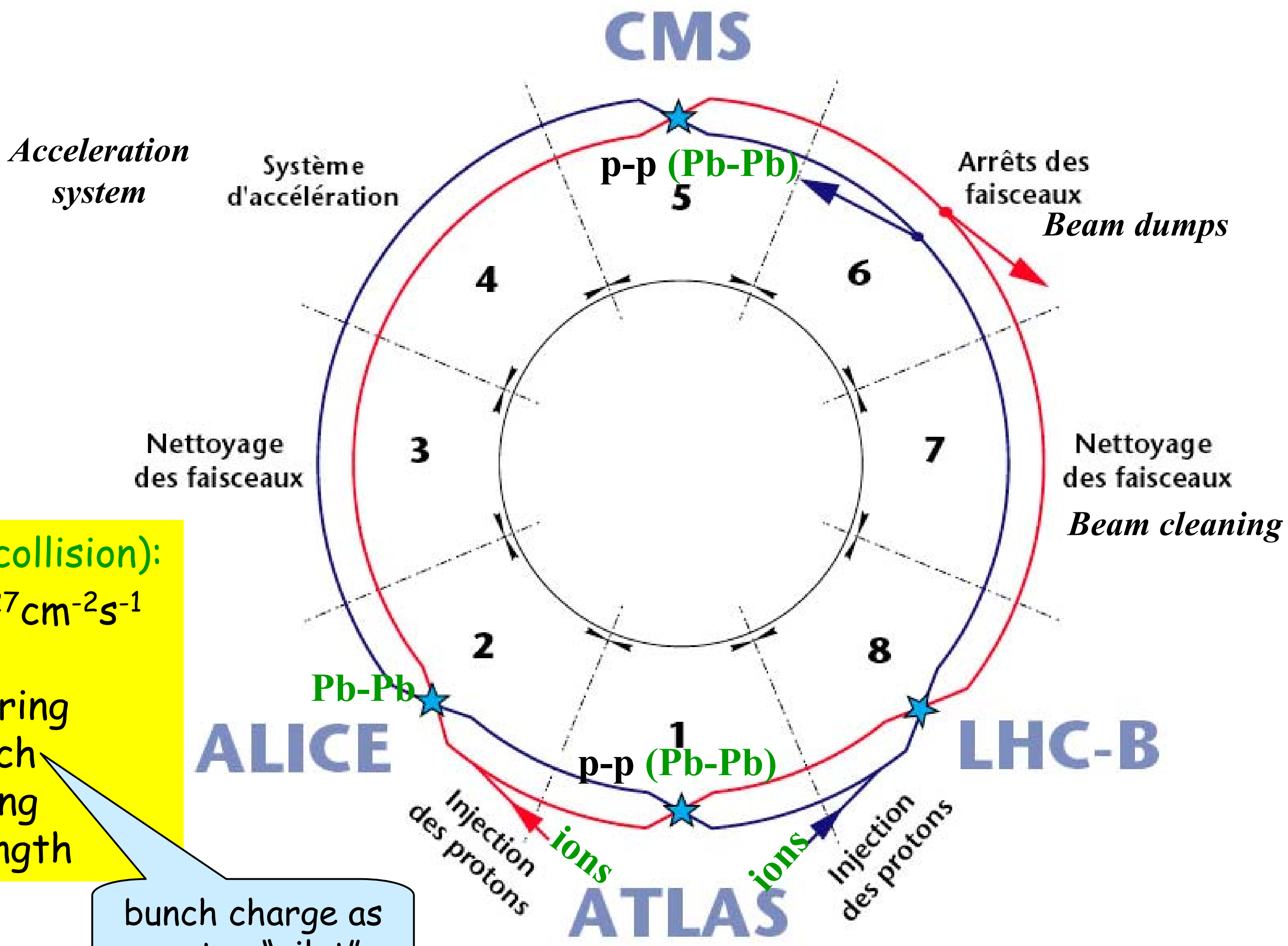
What's Special about Heavy Ions?

- Heavy Nuclei are more fragile than protons when interacting with matter
  - Much higher ionization energy loss
  - Hadronic fragmentation, electromagnetic dissociation
  - Partially Stripped Ions – even more fragile
  - Loss or capture of electrons ➔ ion loss ➔ UHV ($\sim 10^{-12}$ mbar) at low-energy machines
- Heavy ions are more difficult to produce
  - More difficult to ionize (electrons have higher binding energy), therefore
  - Sources for highly ionized heavy ions produce only some 100 μA (protons ~100 mA)
- The SPS has worked with heavy ions (Pb, In) fixed-target physics for many years.

  Why not just taking this beam and send it to the LHC?

  - The LHC luminosity for Pb would miss the nominal figure ($10^{27} cm^{-2} s^{-1}$) by a factor ~1000
  - This factor 1000 (or 30 in beam "brightness") is gained by accumulation (to get higher intensity) and electron cooling (so the beam fits into the tiny LHC emittance) in LEIR.
  - Beam pulses of 200 μA × 200 μs (ion source) transformed to 1A × 1 ns at LHC collision

LHC: Layout



Nominal Pb beam (collision):

Luminosity $L_0 = 10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

2.76 TeV/nucleon

~600 bunches per ring

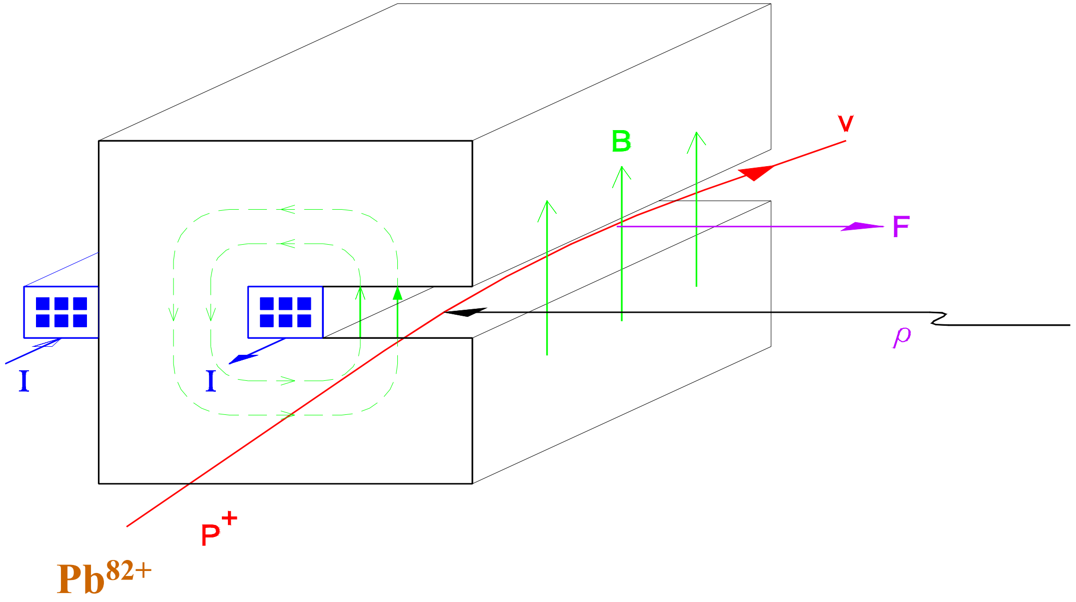
7×10^{7} ions per bunch

100 ns bunch spacing

1 ns total bunch length

bunch charge as proton "pilot"

Magnetic Rigidity : Proton vs. Ion



$$F = evB = \frac{mv^2}{\rho}$$

magnetic rigidity

for protons $$B\rho = \frac{mv}{e} = \frac{m_0\gamma\beta c}{e}$$

for any ion
(charge Qe
mass Am_0)

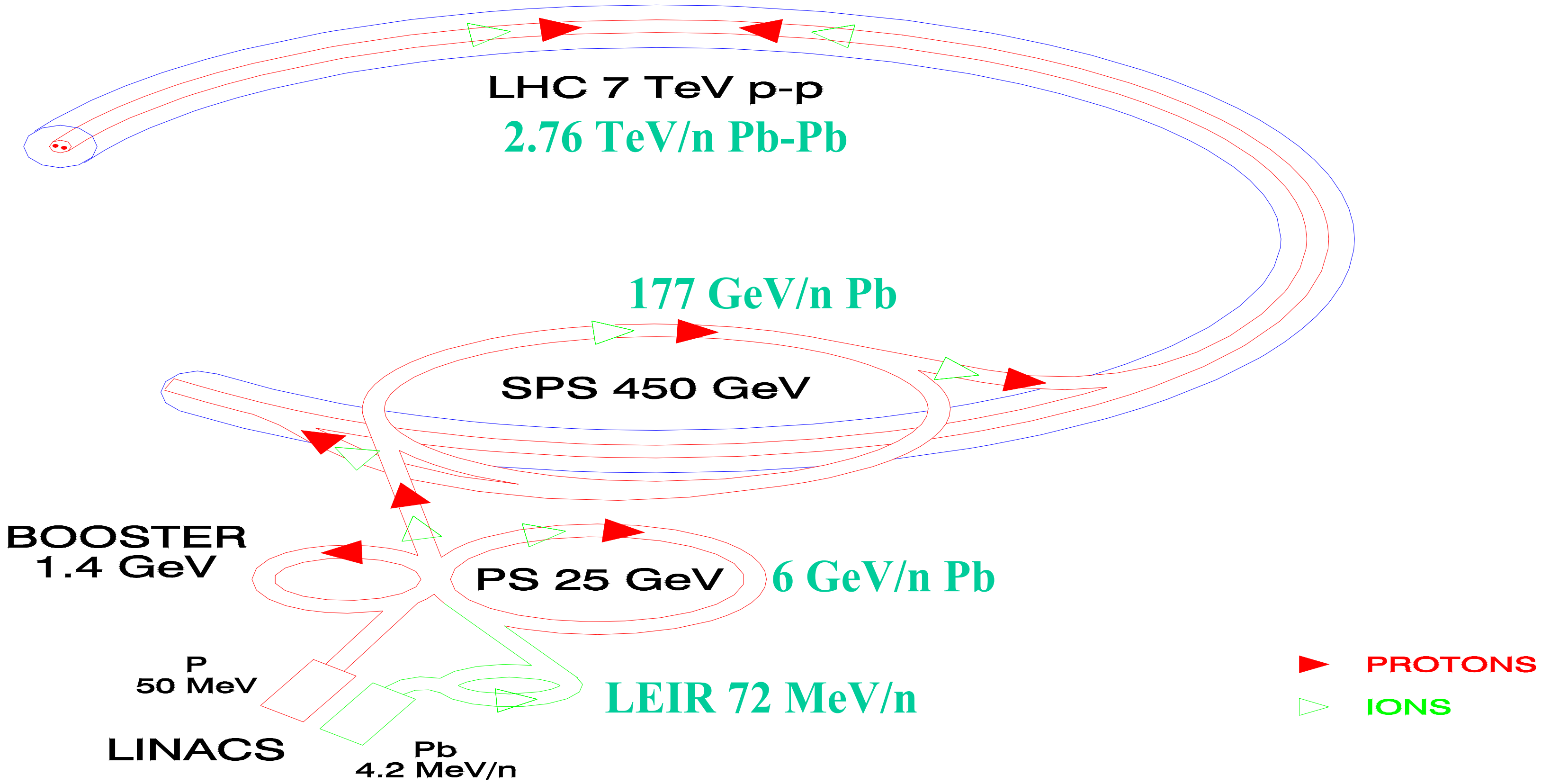
$$\boxed{B\rho = \left(\frac{A}{Q}\right)\frac{m_0\beta\gamma c}{e}}$$

Q/A	Charge-to-mass ratio
m_0	mass of a nucleon
$m_0\beta\gamma c$	momentum/nucleon
$m_0(\gamma-1)c^2$	(kinetic) energy/nucleon

	p	d	α	$_{16}O^{4+}$	$_{208}Pb^{54+}$	$_{208}Pb^{82+}$
Q	1	1	2	4	54	82
A	1	2	4	16	208	208
				partially stripped	partially stripped	fully stripped

momentum/nucleon (GeV/c/n) **(kinetic) energy/nucleon (GeV/n)**			
	SPS injection	**LHC inj.**	**LHC collision**
protons	**26**	**450**	**7000**
$_{208}Pb^{82+}$	**6.75 GeV/c/n**	**178**	**2760**
$_{208}Pb^{82+}$	**5.9 GeV/n**	**177**	**2759**

The LHC Injector Chain - Overview



LHC Pb Injector Chain: Key Parameters

Nominal LHC Pb-Pb Luminosity 10^{27} cm^{-2} s^{-1}

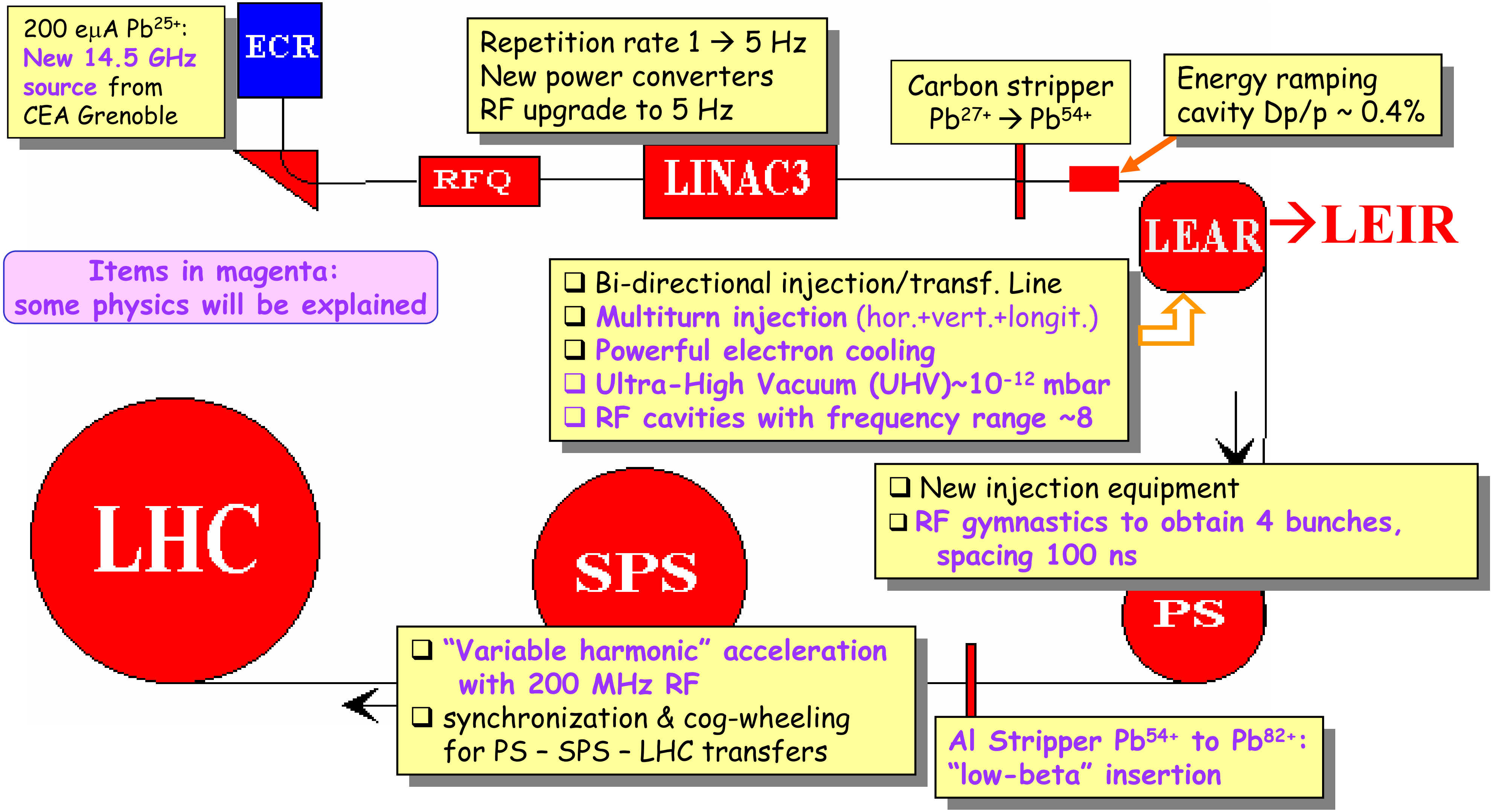
	ECR Source →	Linac 3 → 4 →	LEIR →	PS → 13,12,8 →	SPS → 12 →	LHC
Output energy	2.5 keV/n	4.2 MeV/n	72.2 MeV/n	5.9 GeV/n	177 GeV/n	2.76 TeV/n
Pb charge state	27+	27+ → 54+	54+	54+ → 82+	82+	82+
bunches/ring			2 (1/8 of PS)	4	52,48,32	592
ions/LHC bunch	$9\ 10^{9}$	$1.15\ 10^{9}$	$2.25\ 10^{8}$	$1.2\ 10^{8}$	$9\ 10^{7}$	$7\ 10^{7}$
bunch spacing [ns]				100	100	100
ε*(nor. rms) [μm]	~0.10	0.25	0.7	1.0	1.2	1.5
ε (phys.rms) [μm]	50	2.5	1.75	0.14	0.0063	0.0005
Repetition time [s]	0.2-0.4	0.2-0.4	3.6	3.6	~50	~10'fill/ring

ε*(normalized) = βγ ε (physical)
invariant if no imperfections

Stripping foil

Same physical emittance as
protons – same beam size

Pb Ions for LHC: Hardware Upgrades
Ions for LHC (I-LHC) Project



200 eμA Pb^{25+}:
New 14.5 GHz source from
CEA Grenoble

Repetition rate 1 → 5 Hz
New power converters
RF upgrade to 5 Hz

Carbon stripper
Pb^{27+} → Pb^{54+}

Energy ramping
cavity Dp/p ~ 0.4%

Items in magenta:
some physics will be explained

- ☐ Bi-directional injection/transf. Line
- ☐ Multiturn injection (hor.+vert.+longit.)
- ☐ Powerful electron cooling
- ☐ Ultra-High Vacuum (UHV)~10^{-12} mbar
- ☐ RF cavities with frequency range ~8

- ☐ New injection equipment
- ☐ RF gymnastics to obtain 4 bunches, spacing 100 ns

- ☐ "Variable harmonic" acceleration with 200 MHz RF
- ☐ synchronization & cog-wheeling for PS – SPS – LHC transfers

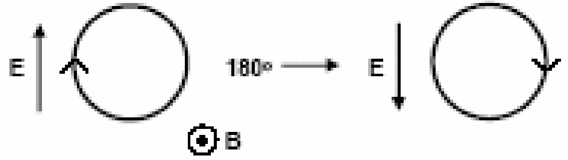
Al Stripper Pb^{54+} to Pb^{82+}:
"low-beta" insertion

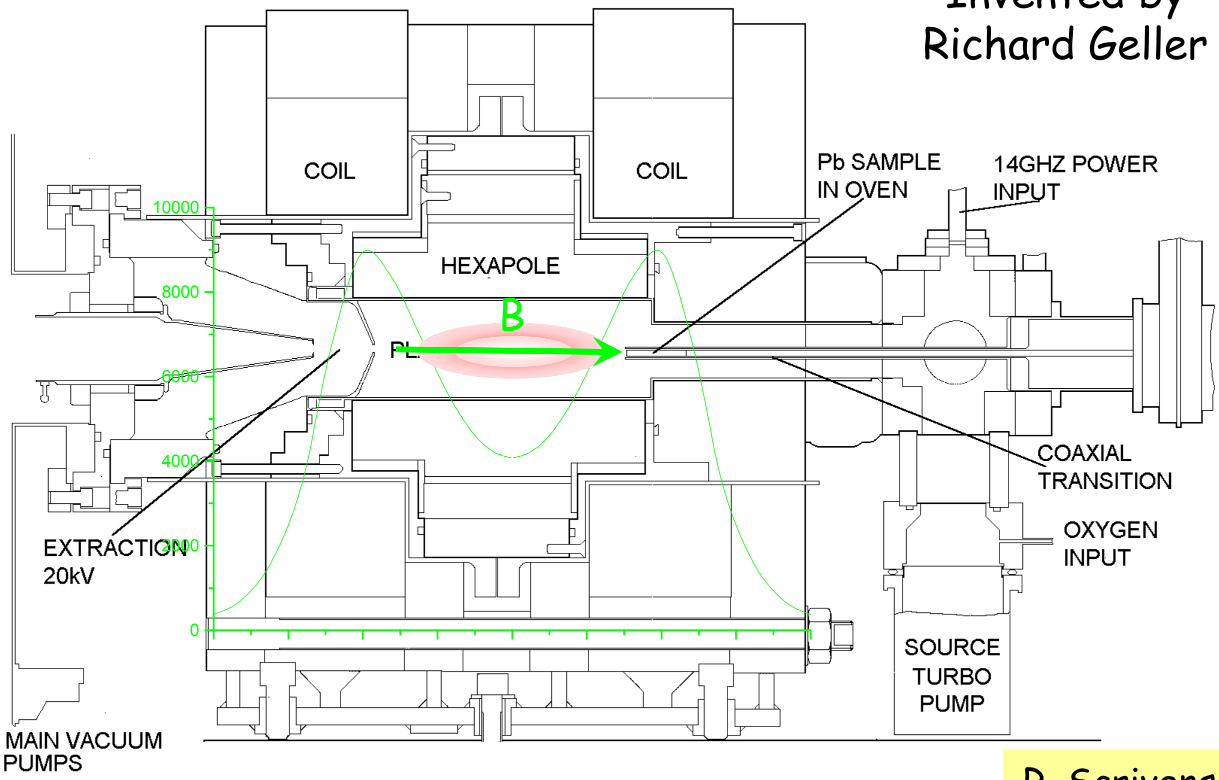
Electron Cyclotron Resonance (ECR) Source – How It Works

- ☐ Electrons (mass m) rotate around static magnetic field lines B with frequency ω_{ecr}
- ☐ electrons are excited by RF with same frequency: their amplitude increases due to the "electron cyclotron resonance"
- ☐ electrons are excited until they leave the Pb atom ➔ ionization to Pb^{27+}

$$\omega_{ecr} = \frac{eB}{m}$$

$$f_{ce}[\mathrm{GHz}] = 2.8 \times B[\mathrm{kG}]$$



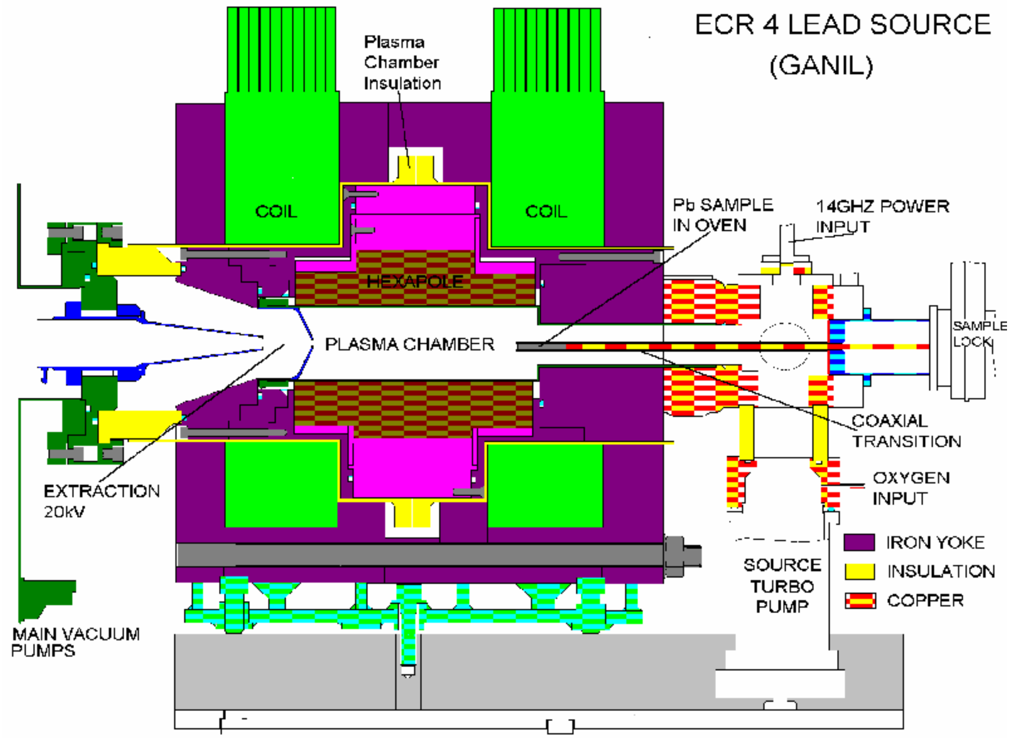


Magnetic bottle: longitudinal and transverse (by "hexapole")

Invented by Richard Geller

R. Scrivens

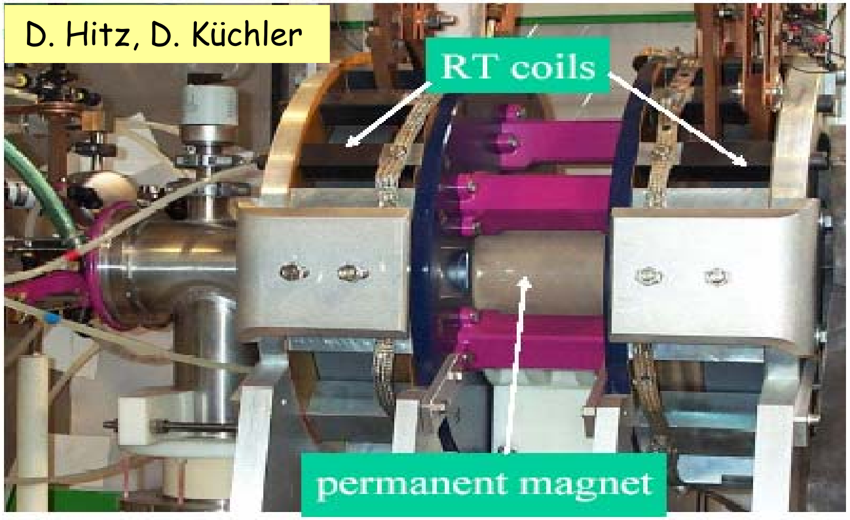
The Heavy Ion (Lead) Linac3 Source



Present ECR (Electron Cyclotron Resonance) Source (used for Pb and In fixed-target physics):

~ 120 eμA × 200 μs Pb^{27+}

OK for LEIR running-in but little margin



D. Hitz, D. Küchler

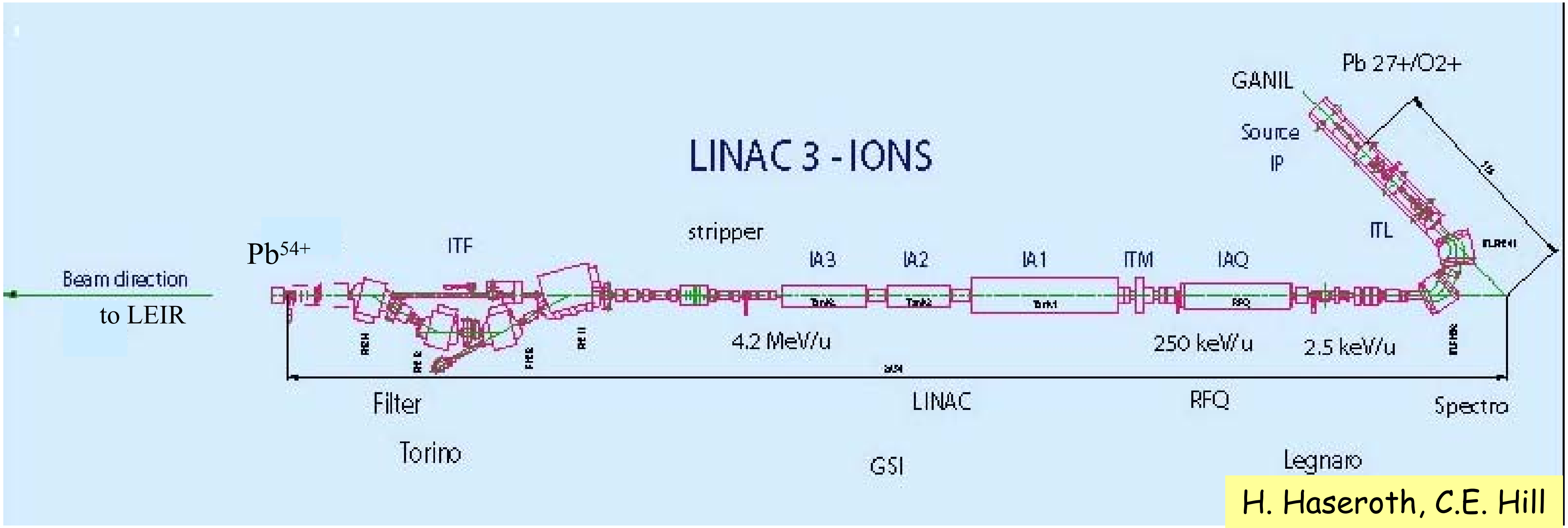
CERN has received an ECR from CEA Grenoble (“Grenoble Test Source”) that is being installed and tested

~ 200 eμA × 200 μs expected

with 14.5 GHz microwave power
extraction energy 2.5 keV/n (β=0.0023)

Required for Nominal Beam

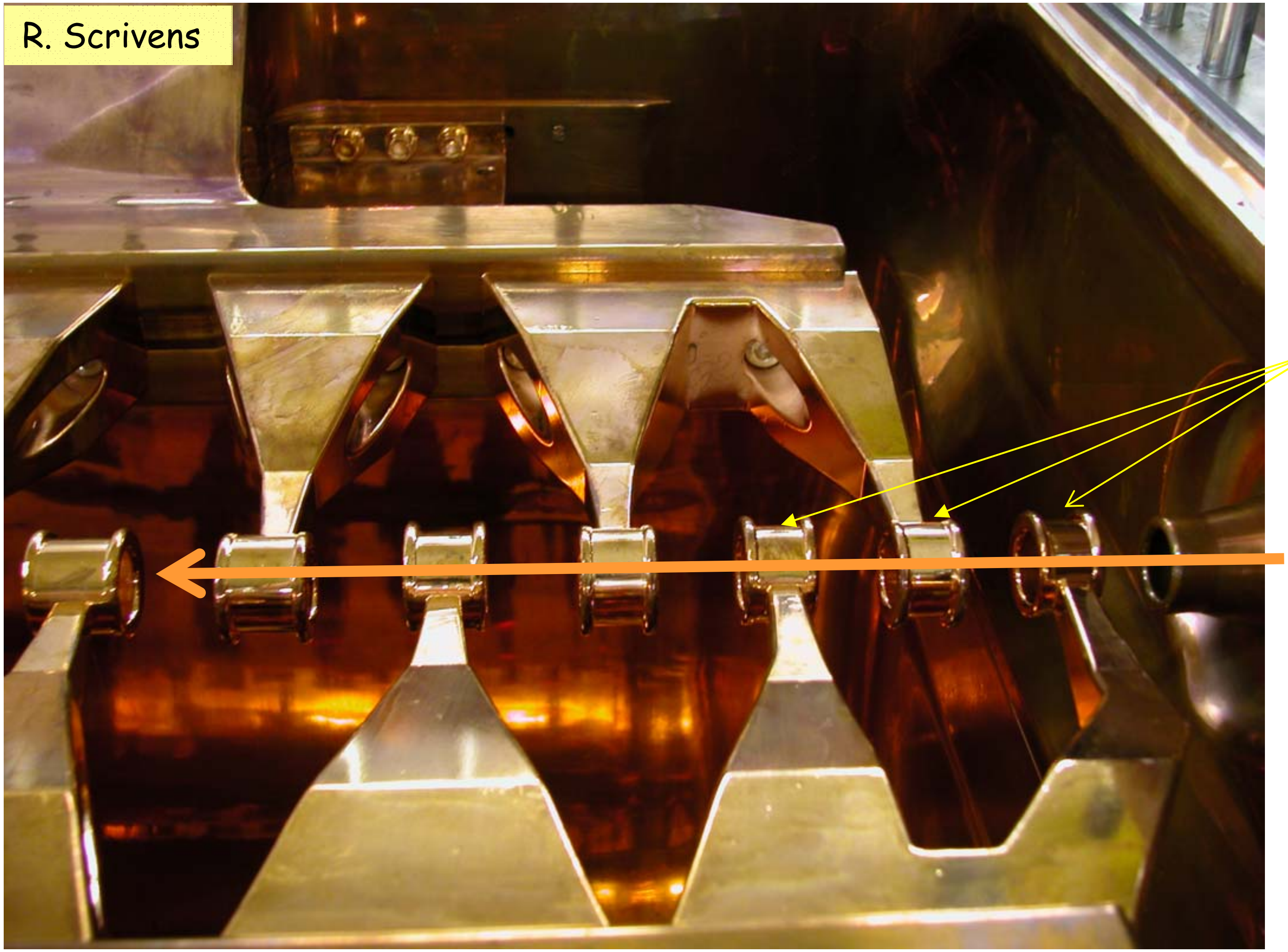
The Heavy Ion (Lead) Linac 3



H. Haseroth, C.E. Hill

- Used for fixed-target ion programme at the SPS since the '90ies (Pb and In)
- Operation at up to 5 Hz to fill LEIR

Tank1 of Linac 3 With Drift Tubes



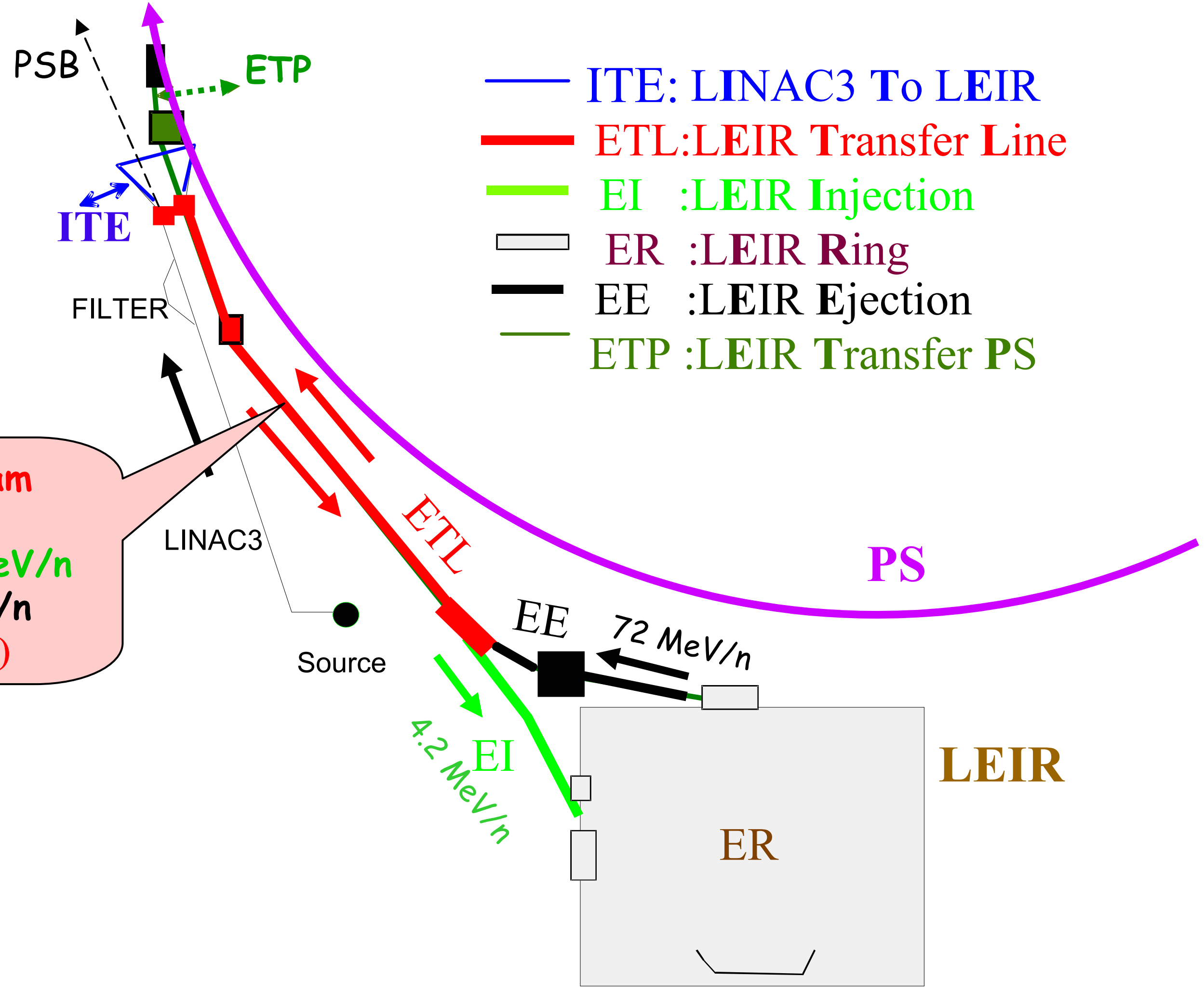
R. Scrivens

Drift tubes and distances between them get longer as ions get faster

Ion beam

$\beta = 0.023$

LINAC3 - LEIR - PS Lines



ITE: LINAC3 To LEIR

ETL:LEIR Transfer Line

EI :LEIR Injection

ER :LEIR Ring

EE :LEIR Ejection

ETP :LEIR Transfer PS

Bi-directional beam transport:

Linac3-LEIR 4.2 MeV/n

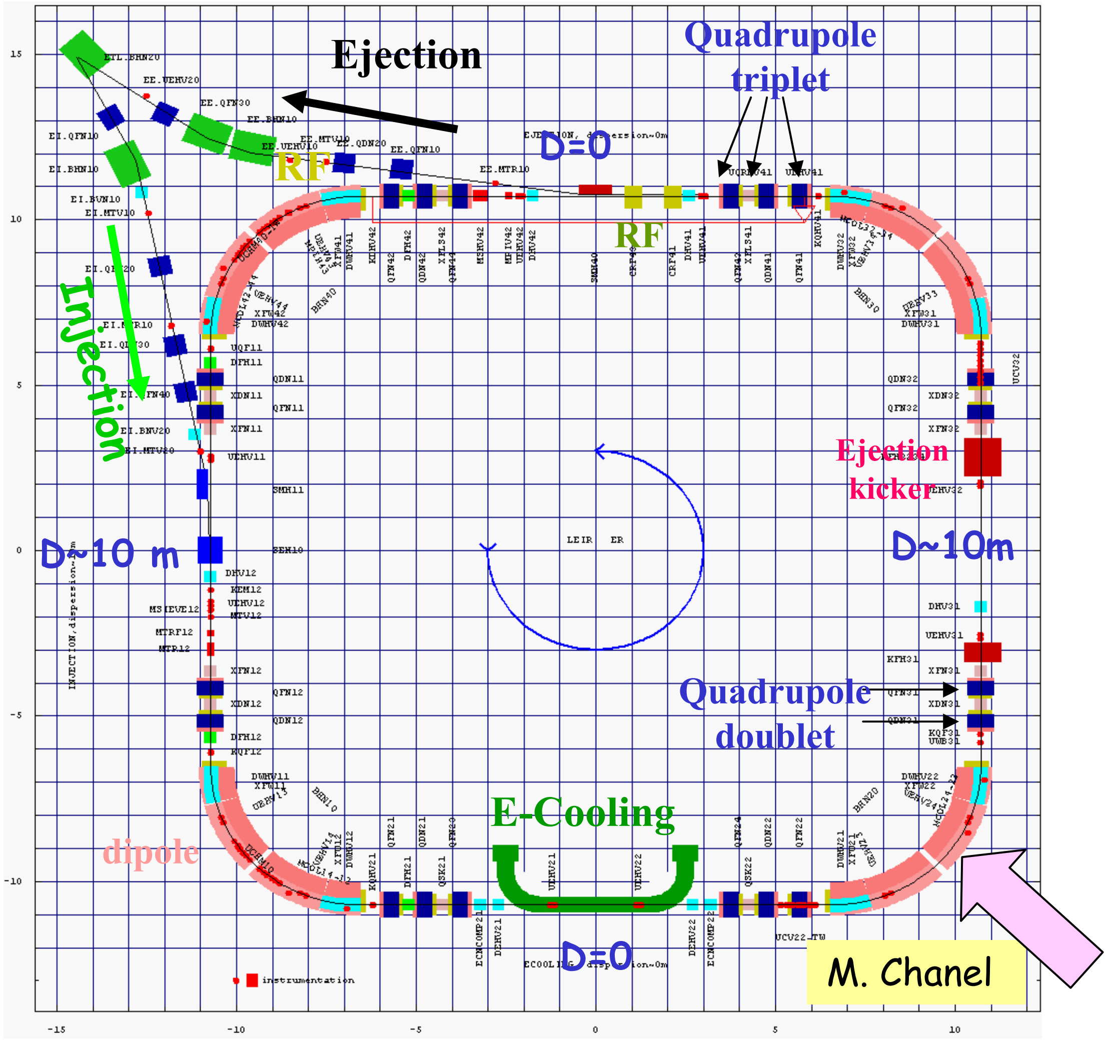
LEIR-PS 72 MeV/n

(factor ~4 in Bρ)

LEIR Layout

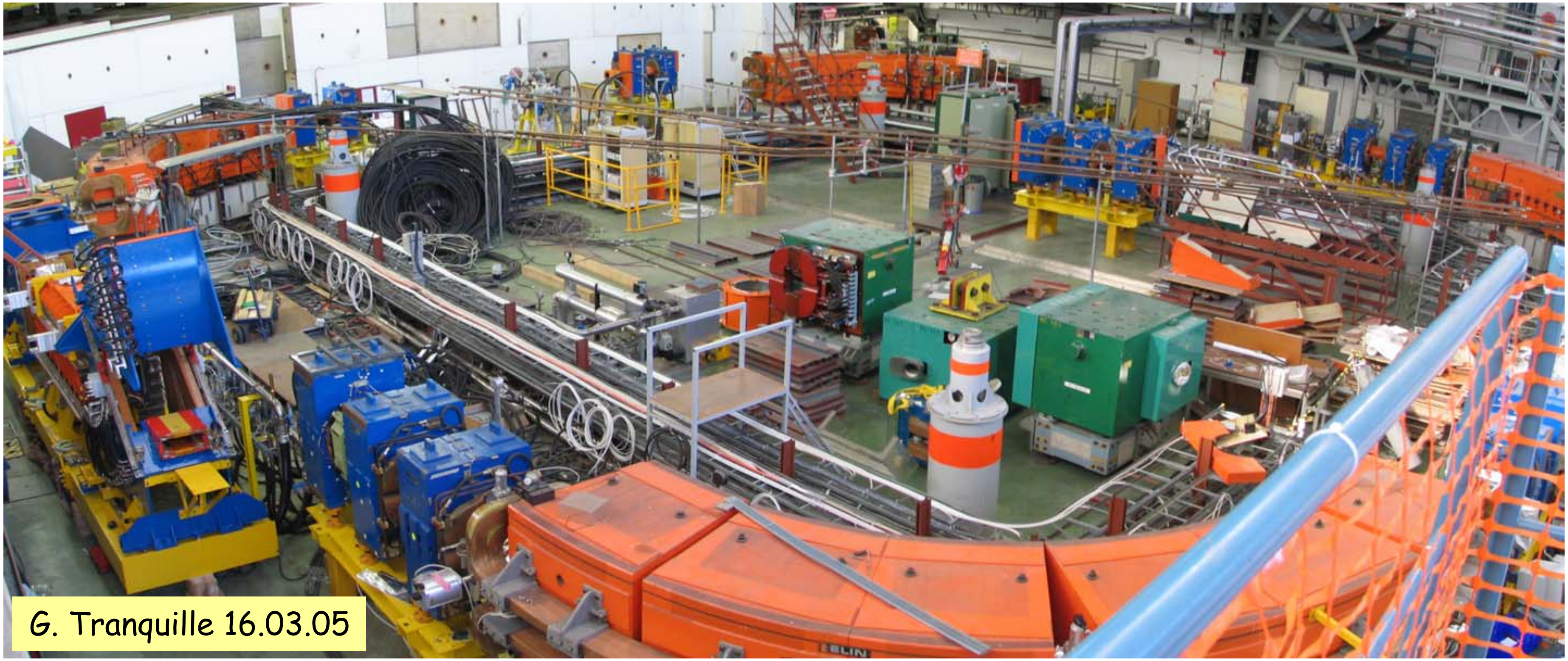
- Lattice with twofold symmetry circumference 25 π m (1/8 PS)
- D (Dispersion) = 0: all ions on same radial position irrespective of their momentum.

  D≠0 (m): Ion radial positions depend on their momentum: $\Delta R = D\,(\Delta p/p)$
- Multiturn injection into hor. + ver. phase planes + longitudinal by energy ramping (0.4 %) during 200μs linac pulse
- Dipole field from 0.27 to 1.15 T
- $(Q_x, Q_y) = (1.82/2.72)$ nominal
- #bunches 2 or 1 (= RF harmonics)
- LEIR Upgrading: ~¾ of I-LHC project resources



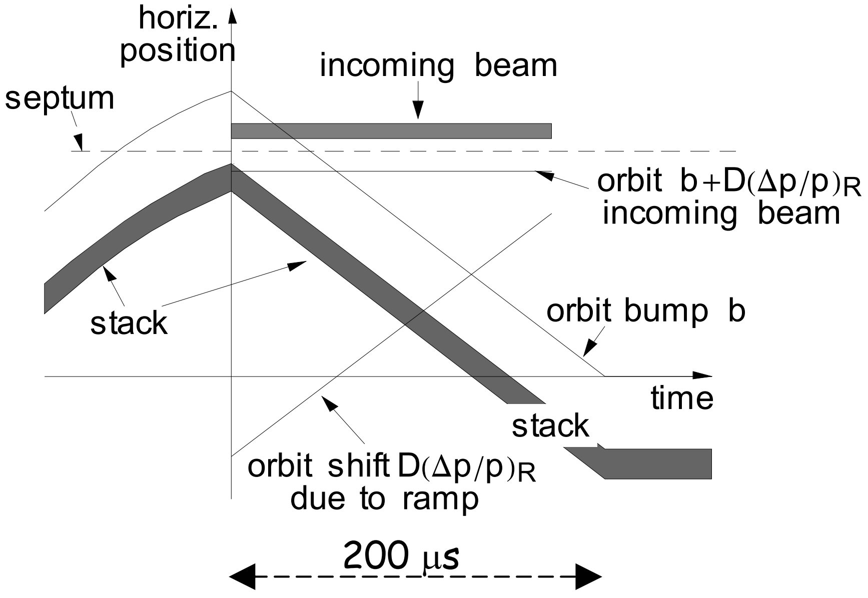
M. Chanel

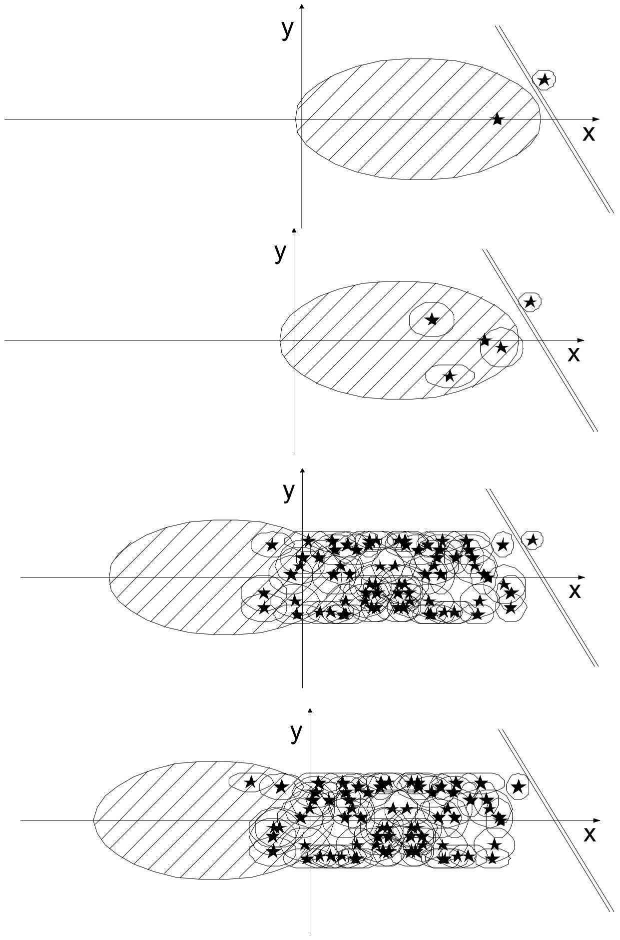
LEIR: Present Status



G. Tranquille 16.03.05

Multiturn Injection into LEIR





1^{st} turn of incoming beam

After 3 turns

End of injection (70 turns)

After collapse of the bump

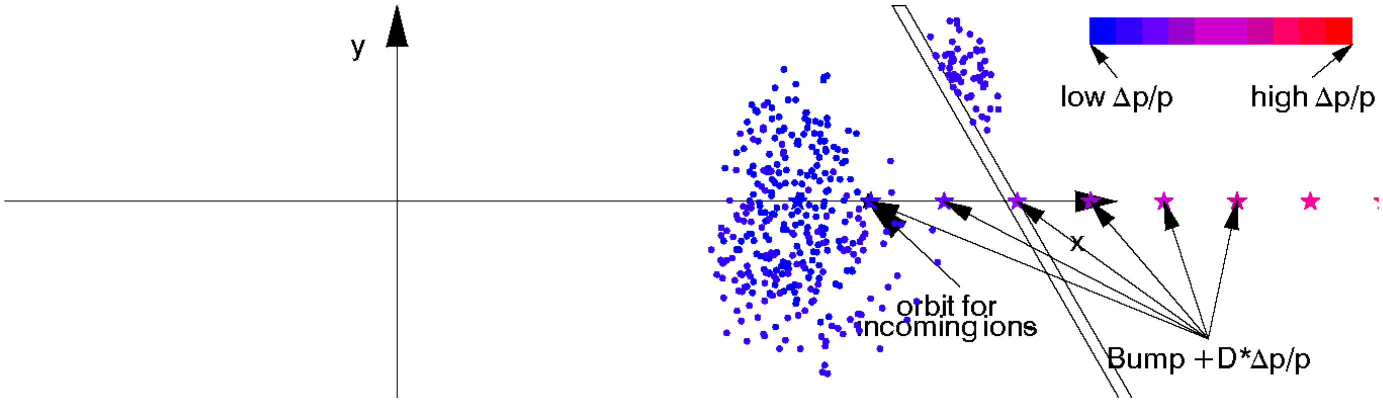
Principle: bumper orbit (and the beam stack) moves inwards while energy ramping moves the orbit of the incoming particles outwards – constant (small) betatron amplitude of incoming beam but large spread in momentum

C. Carli, S.Maury, D.Möhl

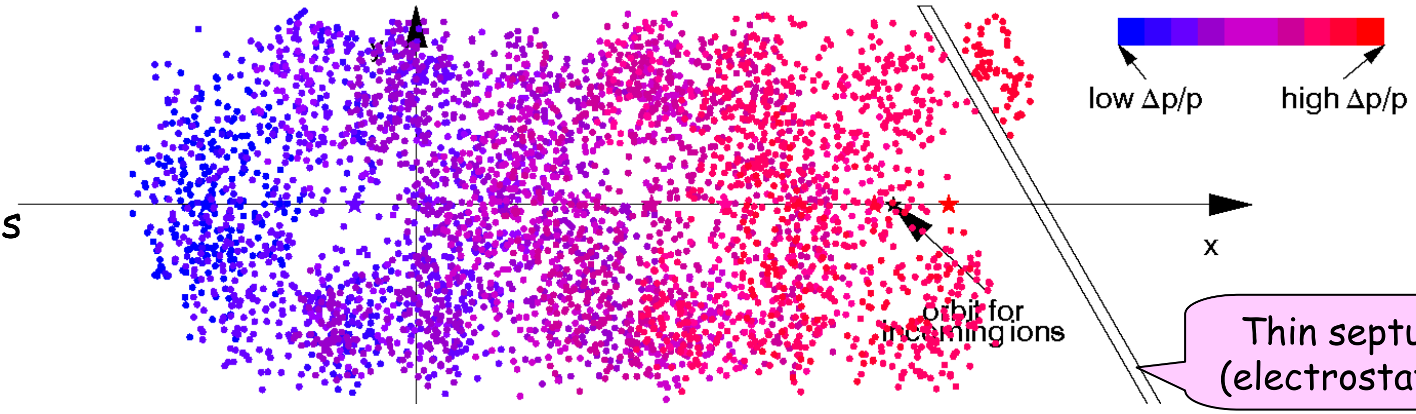
Multiturn Injection in three phase planes

Horizontal/vertical (x/y) plane

injection of the 3rd turn



At the end of the injection after 70 turns

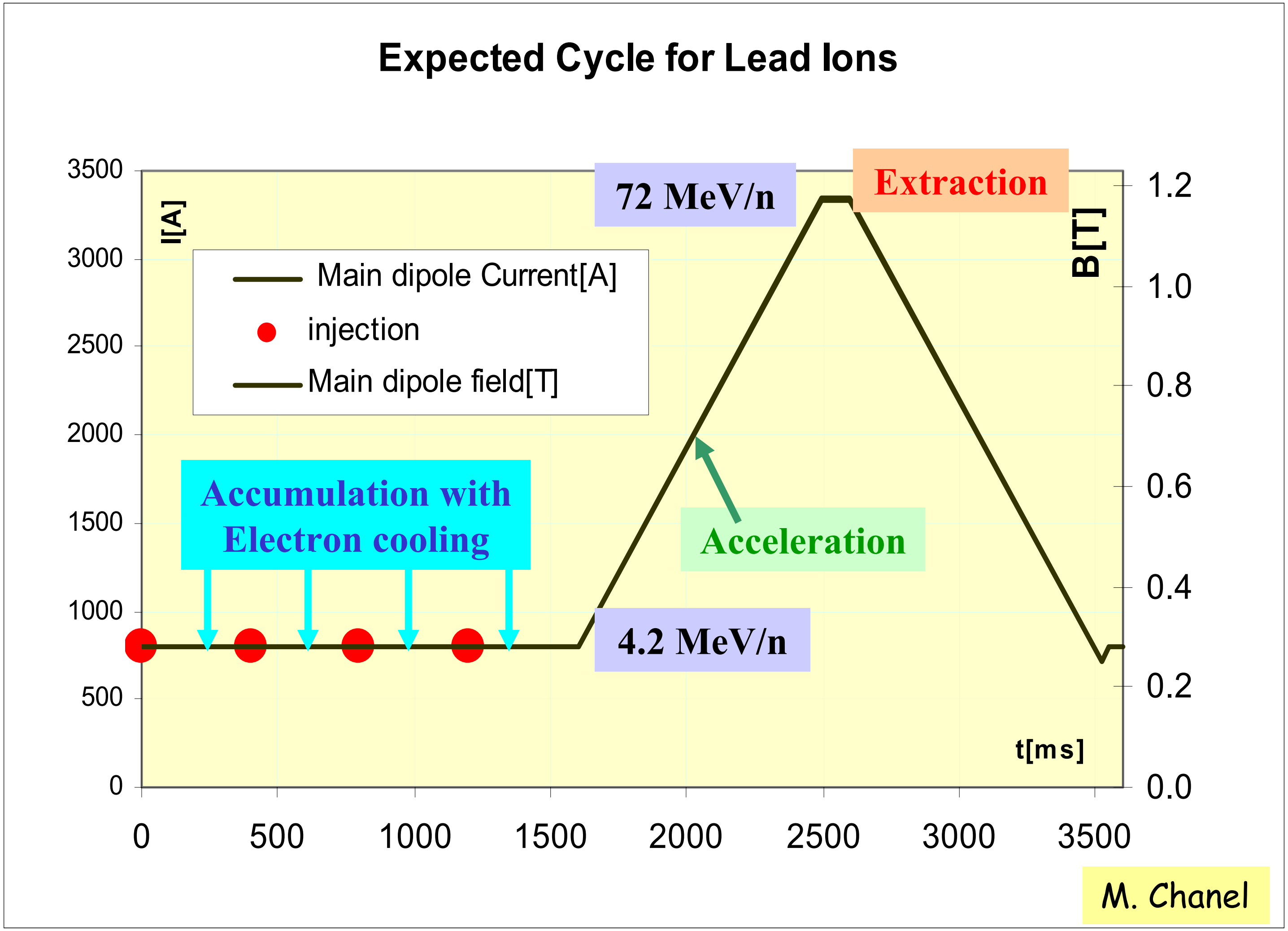


Thin septum (electrostatic)

C. Carli

Injection efficiency ~70%

LEIR Acceleration Cycle



M. Chanel

LEIR Electron Cooler

☐ The electrons have to have the same speed (same β, same γ) as the ions, thus

$$\boxed{T(\text{electrons}) = 1/1823\ T/n\ (\text{ions})}$$

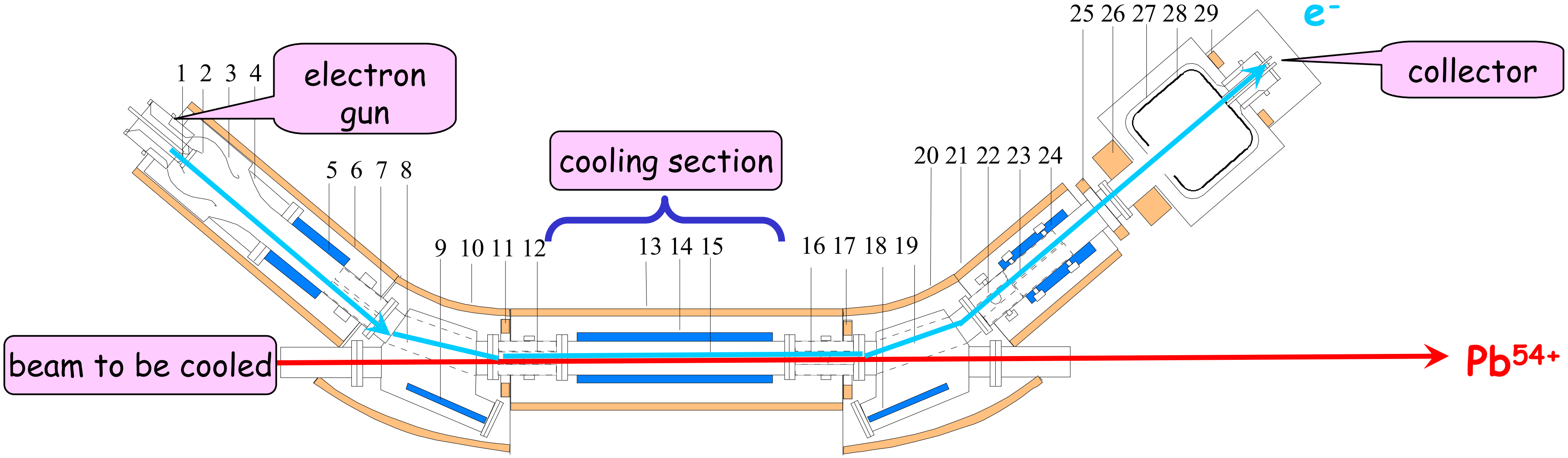
(for example, electrons with kinetic energy T= 2.3 keV cool 4.2 MeV/n ions)

☐ The relative speed of electrons to each other is very small in their common rest frame

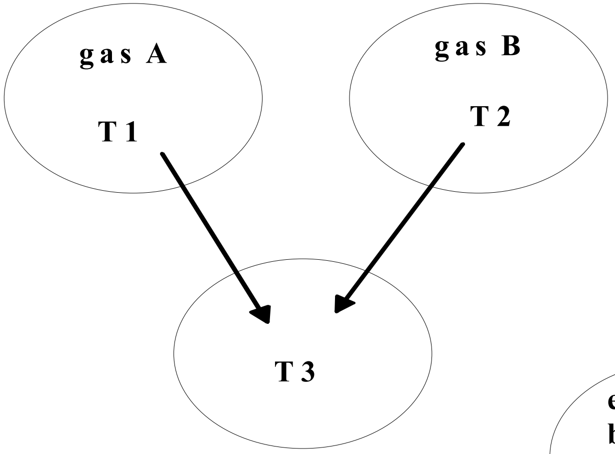
☐ The electrons are focused and kept parallel by longitudinal magnetic fields (solenoids)

☐ Voltage: up to 40 kV (cooling of ions up to 64 MeV/u possible)

☐ electron current (at low energy) 0.05 - 0.6 A



Electron Cooling: How It Works



gas A

T1

gas B

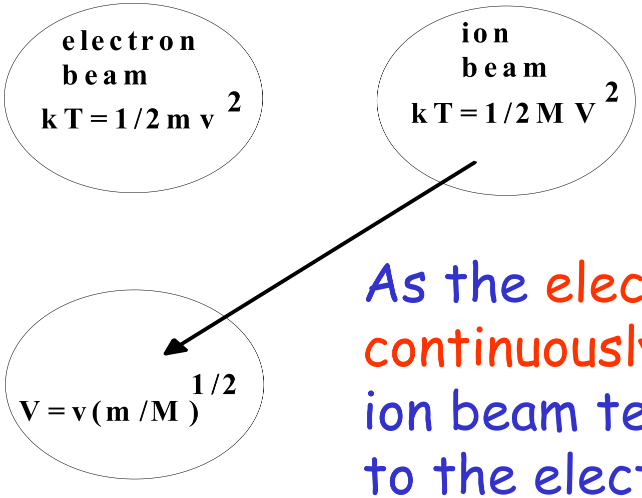
T2

T3

Two gases of different temperatures T1 an T2 tend to an equilibrium temperature T3

Analogy with the mixing of gases

v….transverse velocity of electrons
V….transverse velocity of ions



electron beam

$kT = 1/2\, m v^2$

ion beam

$kT = 1/2\, M V^2$

$V = v(m/M)^{1/2}$

Invented by
Gersh I. Budker

As the electron beam is continuously renewed, the ion beam temperature tends to the electron beam temperature. The velocity spread is reduced by a factor $(m/M)^{1/2}$

G. Tranquille

Electron Cooling Rate

$$\frac{1}{\tau} \propto \frac{I_e \eta}{\theta^3 \gamma^5 \beta^4} \frac{Q^2}{A}$$

higher charge state
⇨ cooling faster

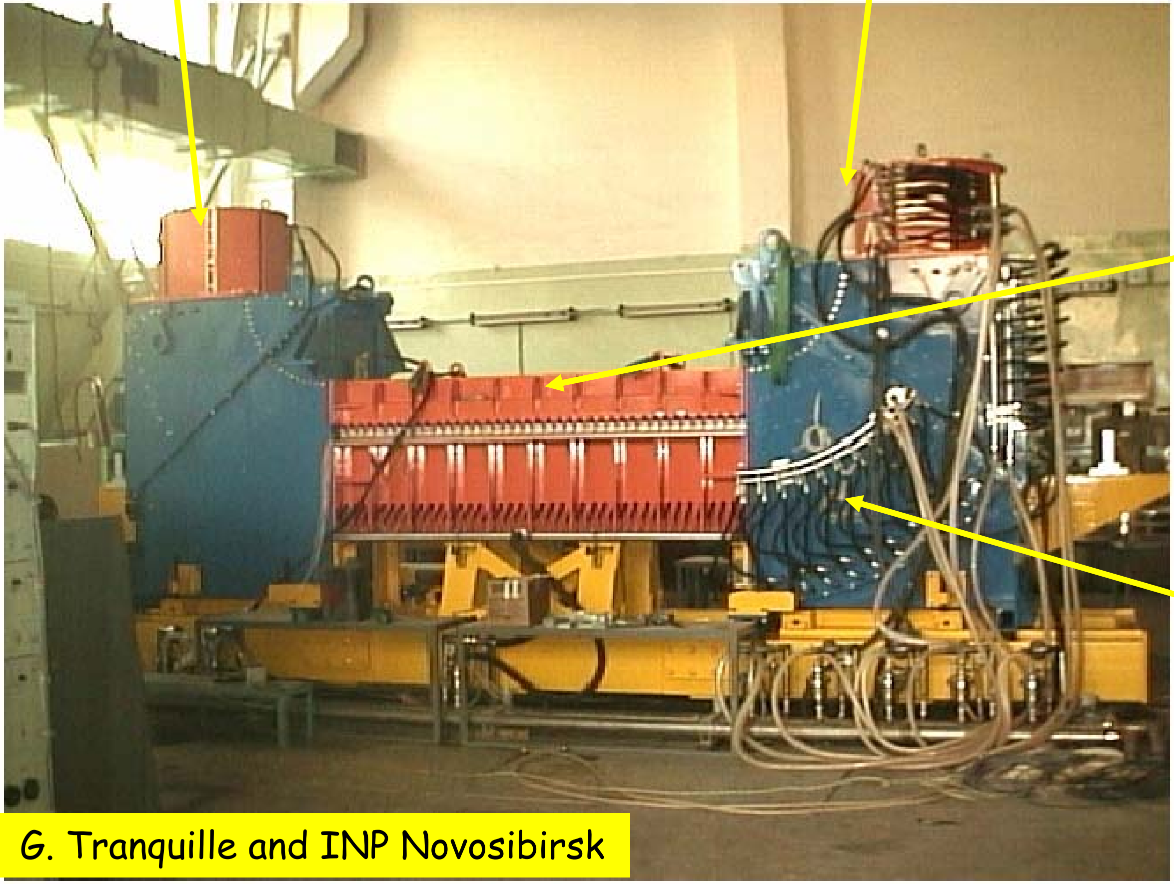
Higher energy ⇨ cooling slower

where $\theta = \theta_{ion} - \theta_{electron}$ difference in angle between the ion and electron beam

$\theta_{electron} = v_{transverse} / v_{longitudinal}$ (with $v_{transverse} \ll v_{longitudinal}$)
$\eta = L_{cooler} / L_{machine}$ (for LEIR $\eta \sim$ 3m/78m)
I_e is the electron current (up to 0.6 A)
β, γ are the relativistic parameters
Q is the ion charge (54 for ${}_{208}Pb^{54+}$ in LEIR)
A atomic mass (208 for ${}_{208}Pb^{54+}$ in LEIR)

Typical cool-down time τ at LEIR injection: some 100 ms

Electron Cooling Made at BINP Novosibirsk



electron gun
(up to 40 kV)
solenoid 6 kG

collector

G. Tranquille and INP Novosibirsk

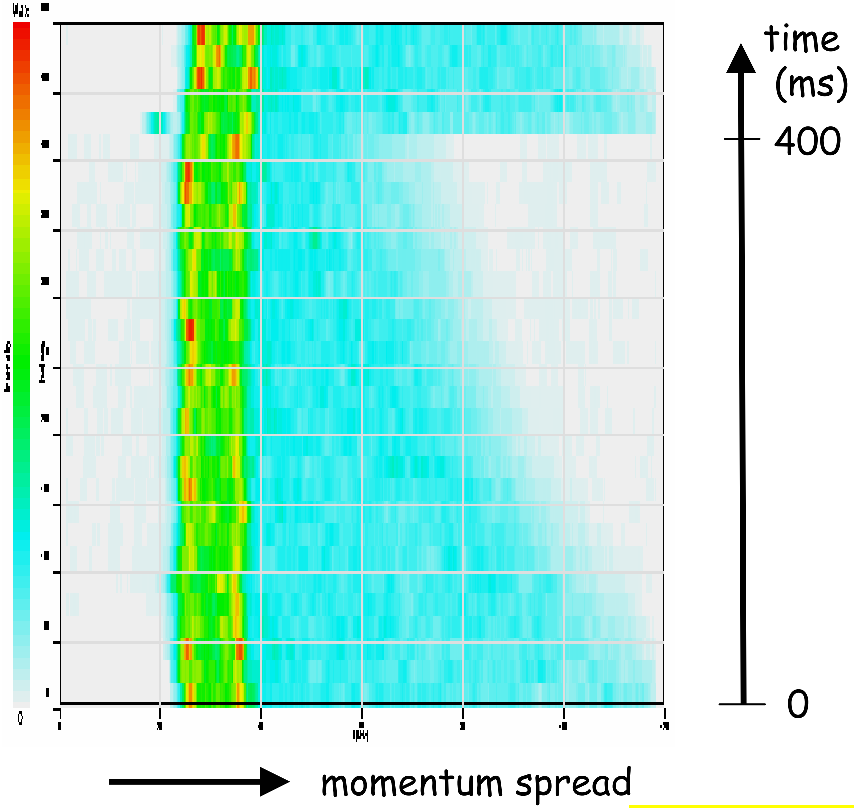
Solenoid 0.75 kG

Toroid 1.5 kG

Accumulation With Electron Cooling

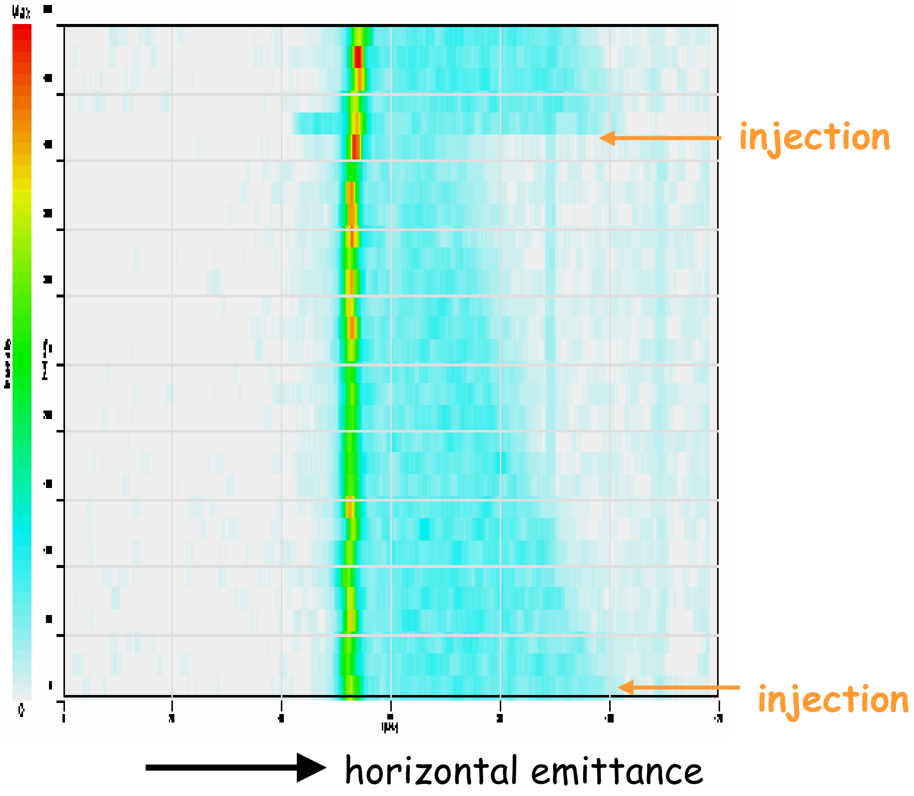
Longitudinal Schottky scan

shows spread in revolution frequency and thus the momentum spread of the ion beam



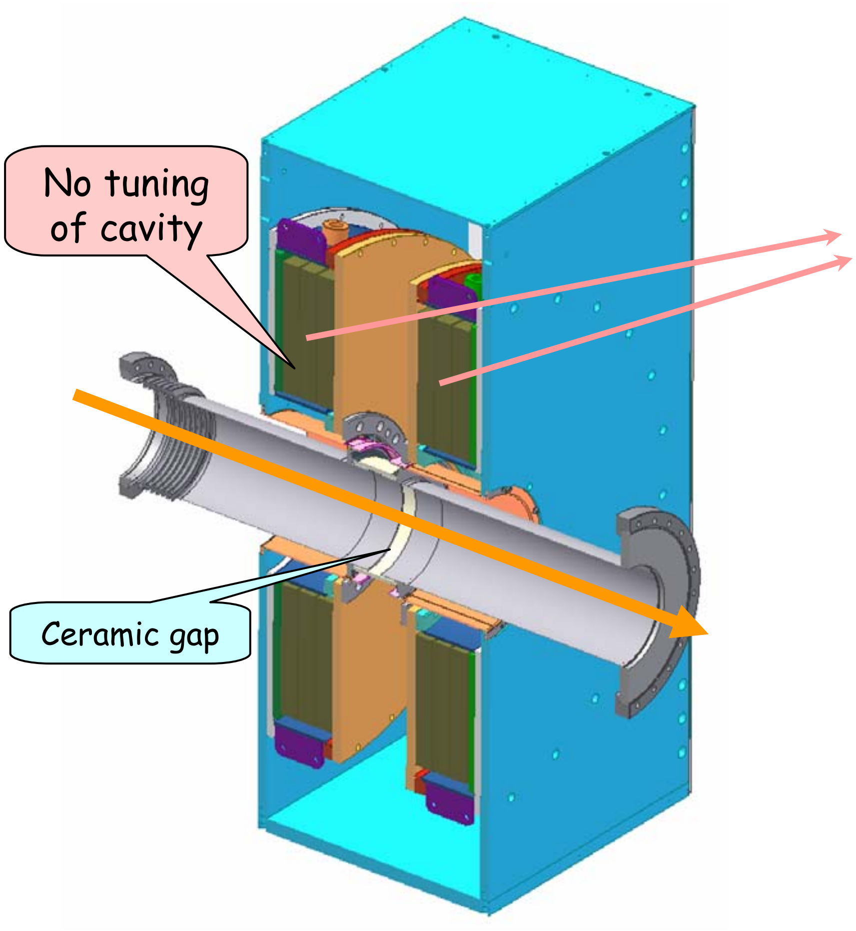
Horizontal Schottky scan

shows horizontal amplitude distribution and thus horizontal emittance



M. Chanel, G. Tranquille, 1997 test results

LEIR RF Acceleration Cavities + Low Level



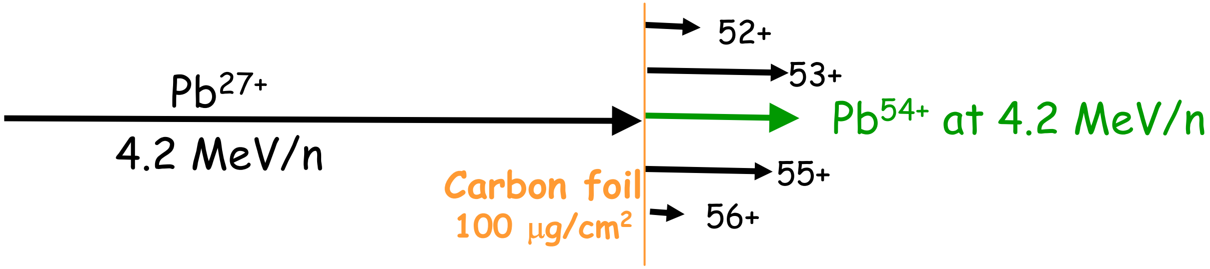
C. Rossi

Two cavities (1 + 1 live spare)
Low voltage (4 kV each)
Frequency swing requirement for Pb
0.36 – 2.84 MHz (h = 1 and 2)
Low-Q Finemet® magnetic ribbon
large band 0.36 – 5 MHz without a "tuner"
(favouring future lighter ions programme…)
RF gap closed during accumulation and cooling
Collaboration with KEK

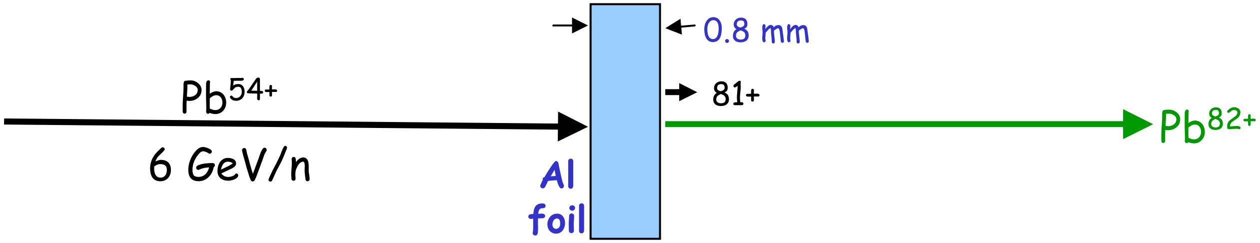
Low-Level RF:
Based on DSP's (Digital Signal Processors)
rather than on conventional analogue circuits
Collaboration with BNL

Stripping – Wanted and Not Wanted

Stripping at 4.2 MeV/n
(Linac3 – LEIR line)
to produce Pb^{54+}

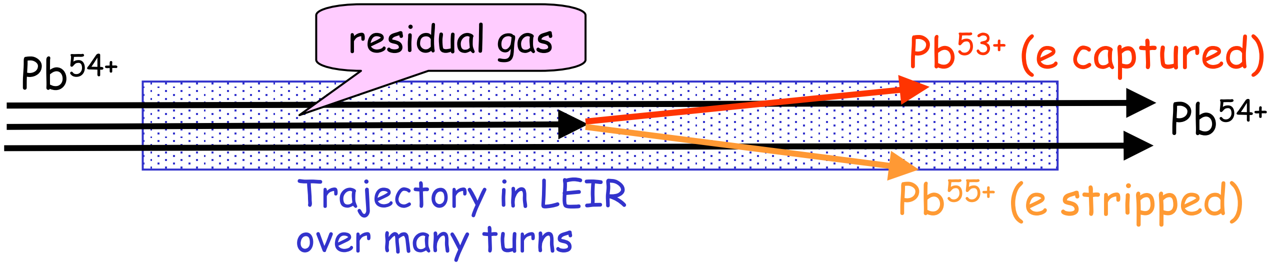


Stripping at 6 GeV/n
(TT2: PS-SPS line)
to produce Pb^{82+}



Pb^{54+} ions capture electrons from residual gas (CO, CO_2, N_2), yielding Pb^{53+} ➔ lost in LEIR because charge/mass different.

Stripping of an electron from Pb^{54+} yields Pb^{55+} lost in LEIR as well

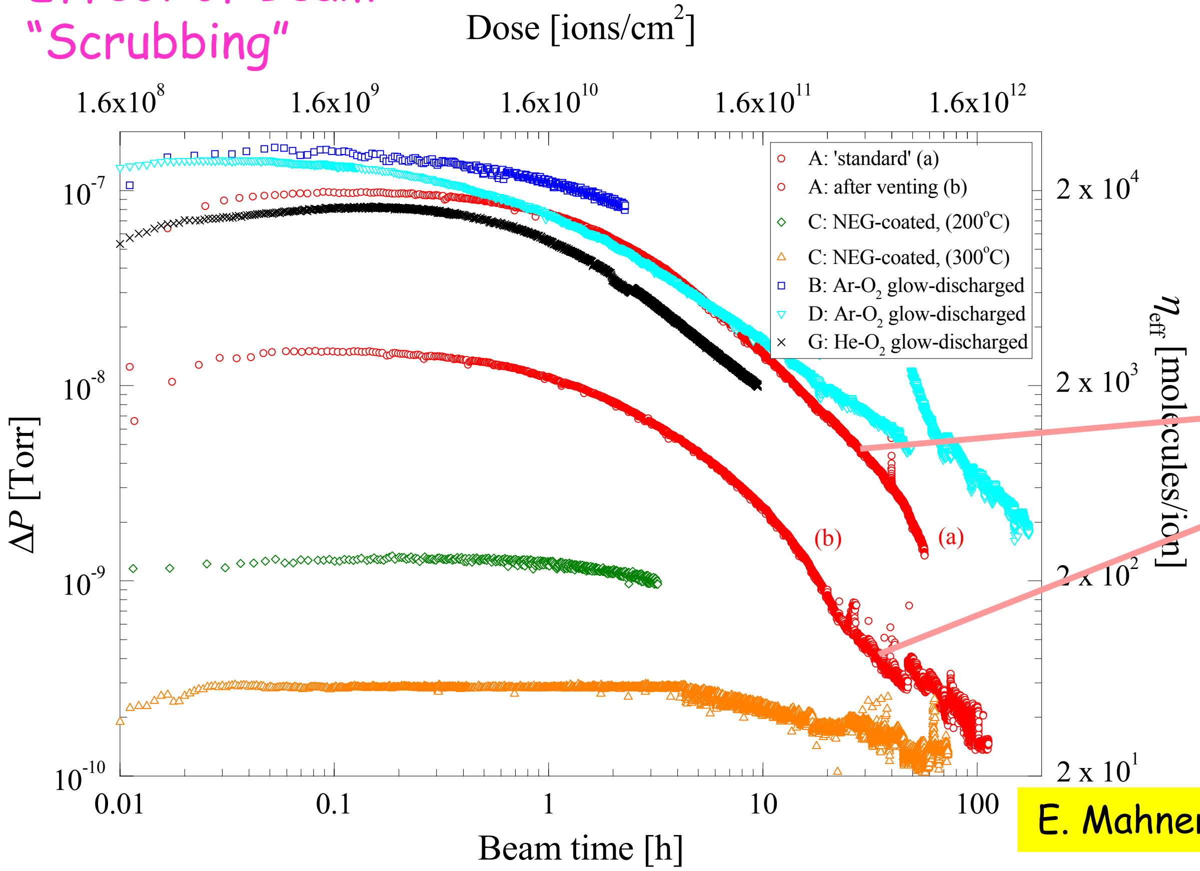


More losses at low energies ➔ UH Vacuum in LEIR

Losses much lower for high energies (SPS, LHC)

LEIR Dynamic Pressure Few 10^{-12} Torr

Effect of Beam "Scrubbing"



E. Mahner

Beam Scrubbing: Tests (Linac 3) with **Pb^{53+} at 4.2 MeV/n**
Various vacuum chambers **"bombarded" with Pb ions**, grazing incidence

Pb^{54+} ions change charge state due to residual gas and are lost

Multi-turn injection loss (~30%): each Pb ion desorbs >10^4 molecules → pressure rise.

But after beam scrubbing, the increase Δp with respect to static pressure almost vanishes

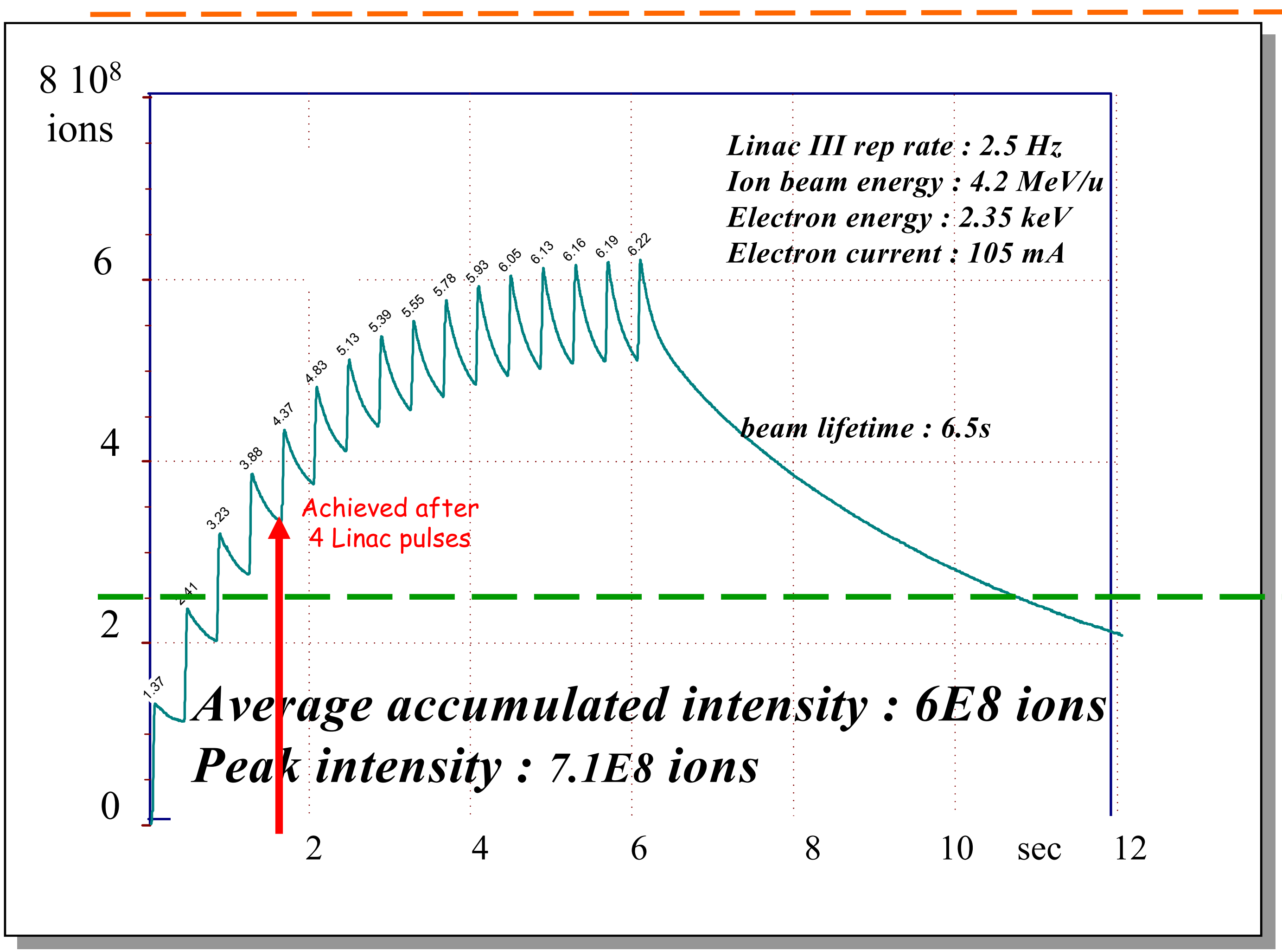
Standard LEIR chamber

Standard chamber after venting

Strategy for ~10^{-12} Torr

- Beam scrubbing will be used
- Non-Evaporable Getter (NEG) coating wherever feasible
- NEG-coated collimators in bending magnets to stop Pb^{53+}
- Vacuum beam lifetime ~30 s
  Overall lifetime ~15 s

Pb Accumulation Test in LEAR 1997



Linac III rep rate : 2.5 Hz
Ion beam energy : 4.2 MeV/u
Electron energy : 2.35 keV
Electron current : 105 mA

Achieved after
4 Linac pulses

Average accumulated intensity : 6E8 ions
Peak intensity : 7.1E8 ions

LEIR nominal

LEIR “Early Beam”

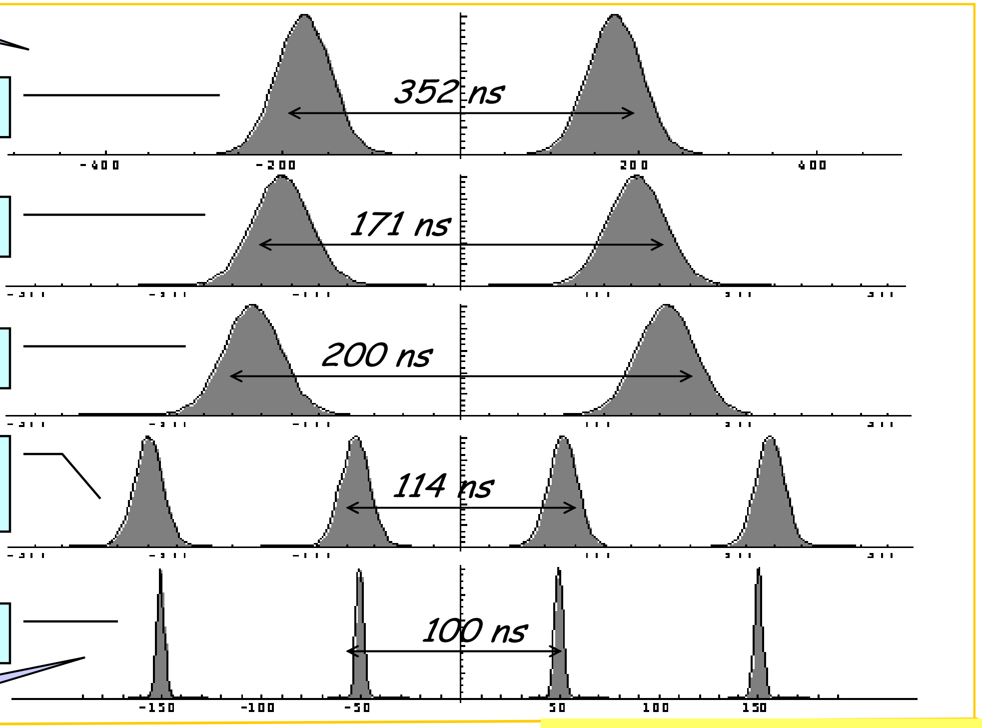
Improvements for LEIR

- ☐ twice the linac intensity
- ☐ faster electron cooling
- ☐ better beam life time (vacuum, etc) of ~15 s

RF Gymnastics in the PS for Pb ions

2 bunches
from LEIR....

¼ of PS circumference



Injection h=16

h=16 to h=14

h=14 to h=12

Splitting h=24
h=24 to h=21

h=21 to h=169

72.2 MeV/n

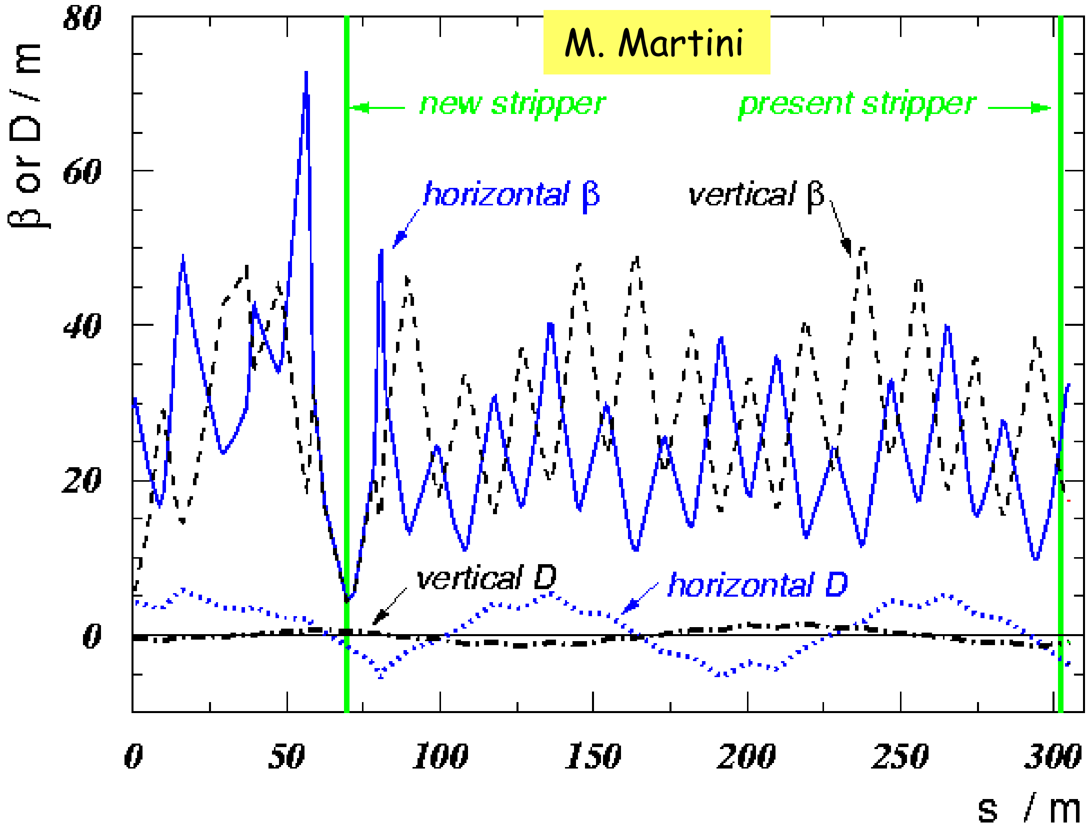
1.0 GeV/n

5.9 GeV/n

....yield 4 bunches for
the LHC, 100 ns spacing

R. Garoby, S. Hancock

PS-SPS Line: Low-β Insertion at Stripper

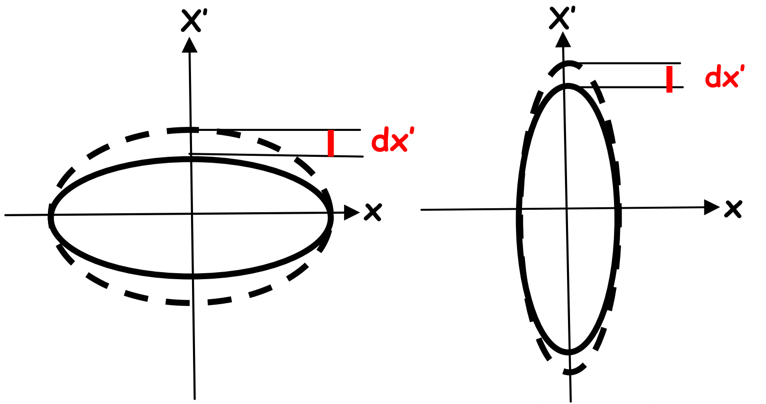


M. Martini

PS → SPS: Stripper foil (Al, 0.8 mm)
Pb^{54+} → Pb^{82+}

Coulomb scattering in the foil: 75% emittance blow-up at present stripper location, reduced to ~10% if foil is at "low β" (both planes).

New optics generates "low-β insertion" at the foil in a new location, thus reducing beta from ~23 to ~4,5 m



"high-β"
large blow-up

"low-β"
small blow-up

Reminder: Beam half-width = $(\beta\ \varepsilon)^{1/2}$

optical

Pb Ions in the SPS: Space Charge

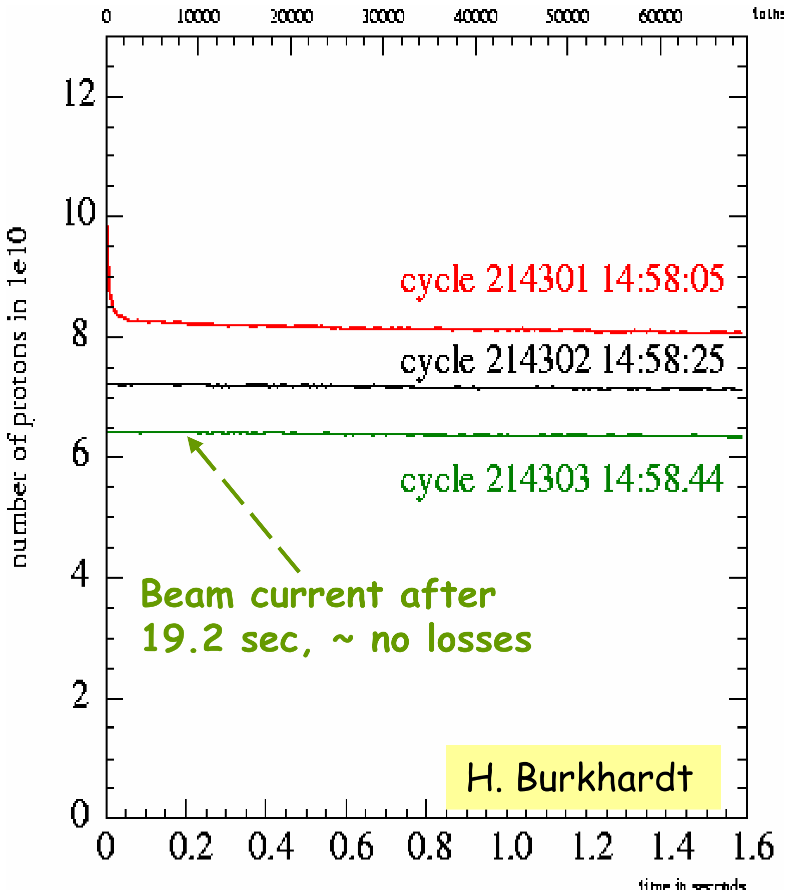
- ☐ **Injection plateau** with up to 13 PS batches (4 bunches each) injected, **lasting 43.2 s. Small transverse blow-up** allowed

- ☐ Pb ions intensity/emittance ratio **("brilliance")** is **limited by space charge** on the injection porch

- ☐ Characteristic for this effect is the **space charge "detuning ΔQ"**:
  - **0.082** calculated **for the nominal Pb ion** beam
  - **P-Pbar** experience: **ΔQ < 0.07**.
  - Recent measurements: **ΔQ ~ 0.2 acceptable**

Reminder
$$\Delta Q \propto \frac{N_b}{\beta\gamma^2\varepsilon_{norm}}$$

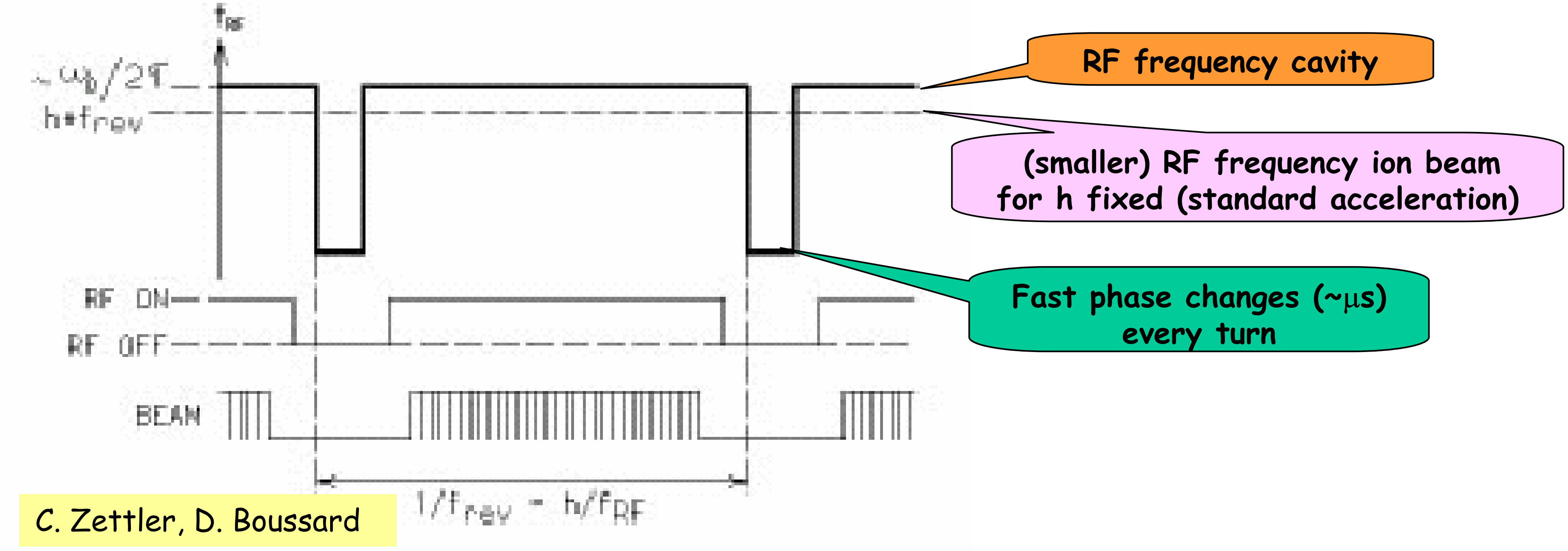
Ions/bunch



Beam current after 19.2 sec, ~ no losses

H. Burkhardt

Ions in SPS: Acceleration



RF frequency cavity

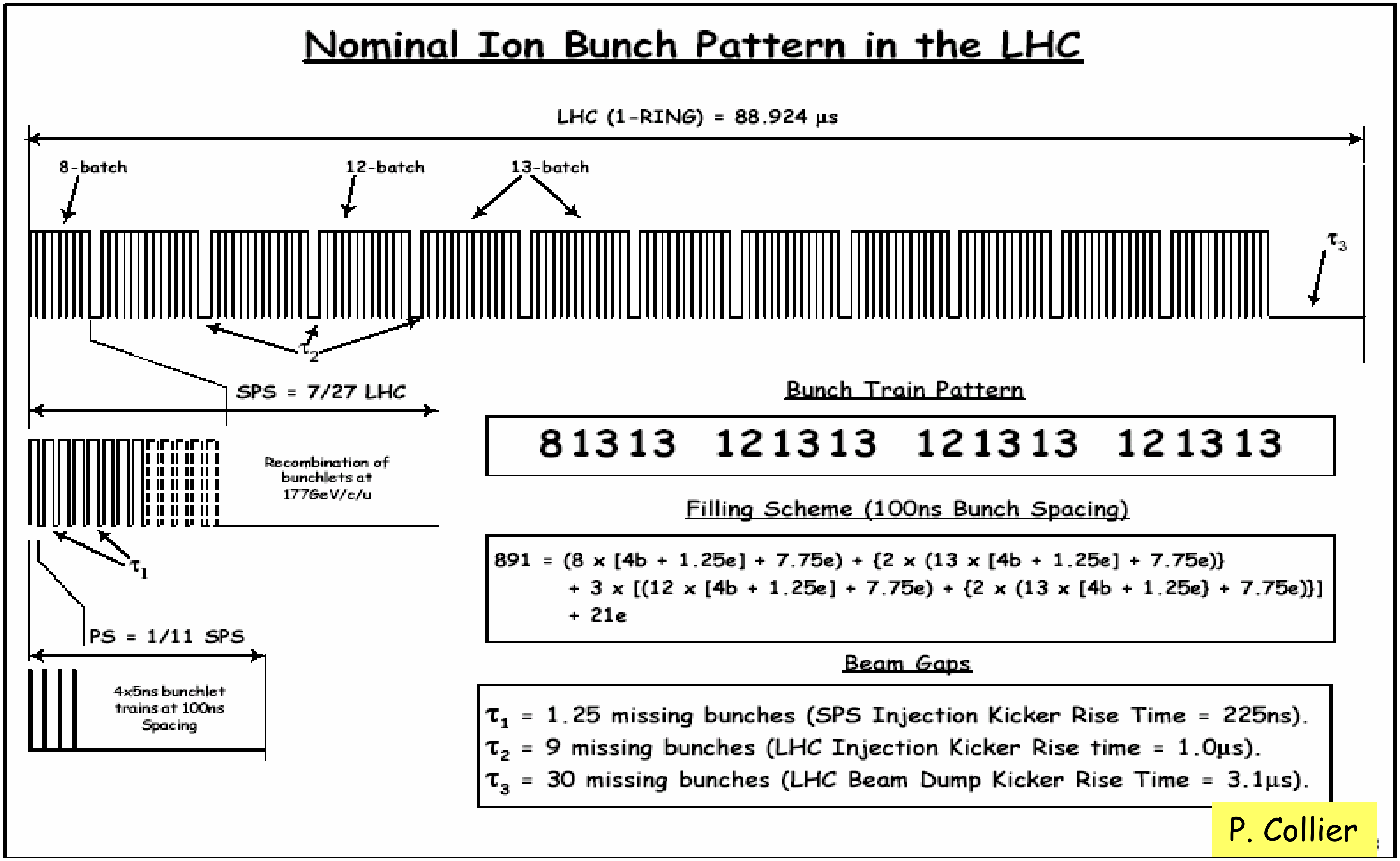
(smaller) RF frequency ion beam for h fixed (standard acceleration)

Fast phase changes (~μs) every turn

C. Zettler, D. Boussard

- ☐ Standard acceleration method: frequency variable, harmonic number h fixed, acceleration cavity "tuned" to the variable frequency
- ☐ Problem with heavy ions: 200 MHz RF system frequency range not compatible with ion frequency swing
- ☐ Solution: frequency fixed, harmonic number h variable
- ☐ Scheme used during SPS ion fixed-target physics (Pb, In)

Pb Ion Pattern in PS-SPS-LHC



Bunch Train Pattern

81313 121313 121313 121313

Filling Scheme (100ns Bunch Spacing)

891 = (8 x [4b + 1.25e] + 7.75e) + {2 x (13 x [4b + 1.25e] + 7.75e)}
+ 3 x [(12 x [4b + 1.25e] + 7.75e) + {2 x (13 x [4b + 1.25e} + 7.75e)}]
+ 21e

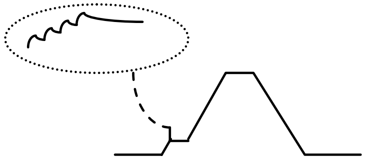
Beam Gaps

τ_1 = 1.25 missing bunches (SPS Injection Kicker Rise Time = 225ns).
τ_2 = 9 missing bunches (LHC Injection Kicker Rise time = 1.0µs).
τ_3 = 30 missing bunches (LHC Beam Dump Kicker Rise Time = 3.1µs).

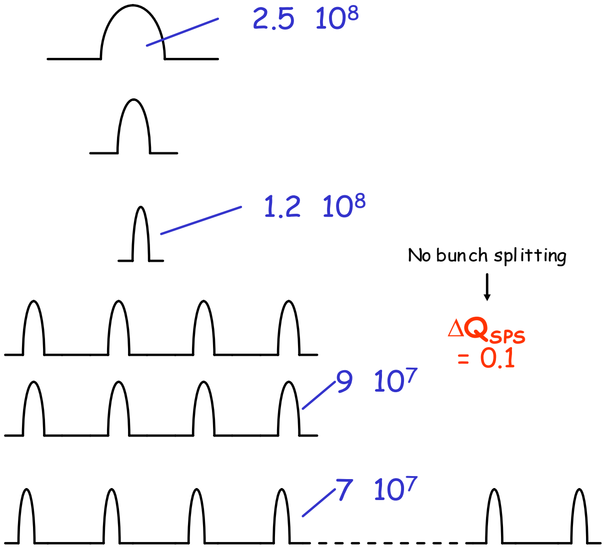
P. Collier

Pb Ions for LHC: Early Operation Scheme

- Luminosity $L=5\ 10^{25}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (factor 20 less): fewer bunches (factor 10) and $\beta^*=1$ m (factor 2)
- Keep nominal bunch population ($7\ 10^7$ ions/bunch) to study limitations without risks
- L allows early Physics discoveries
- much easier for injectors (LEIR, PS)
- improved luminosity lifetime because of larger β^*



1 injection

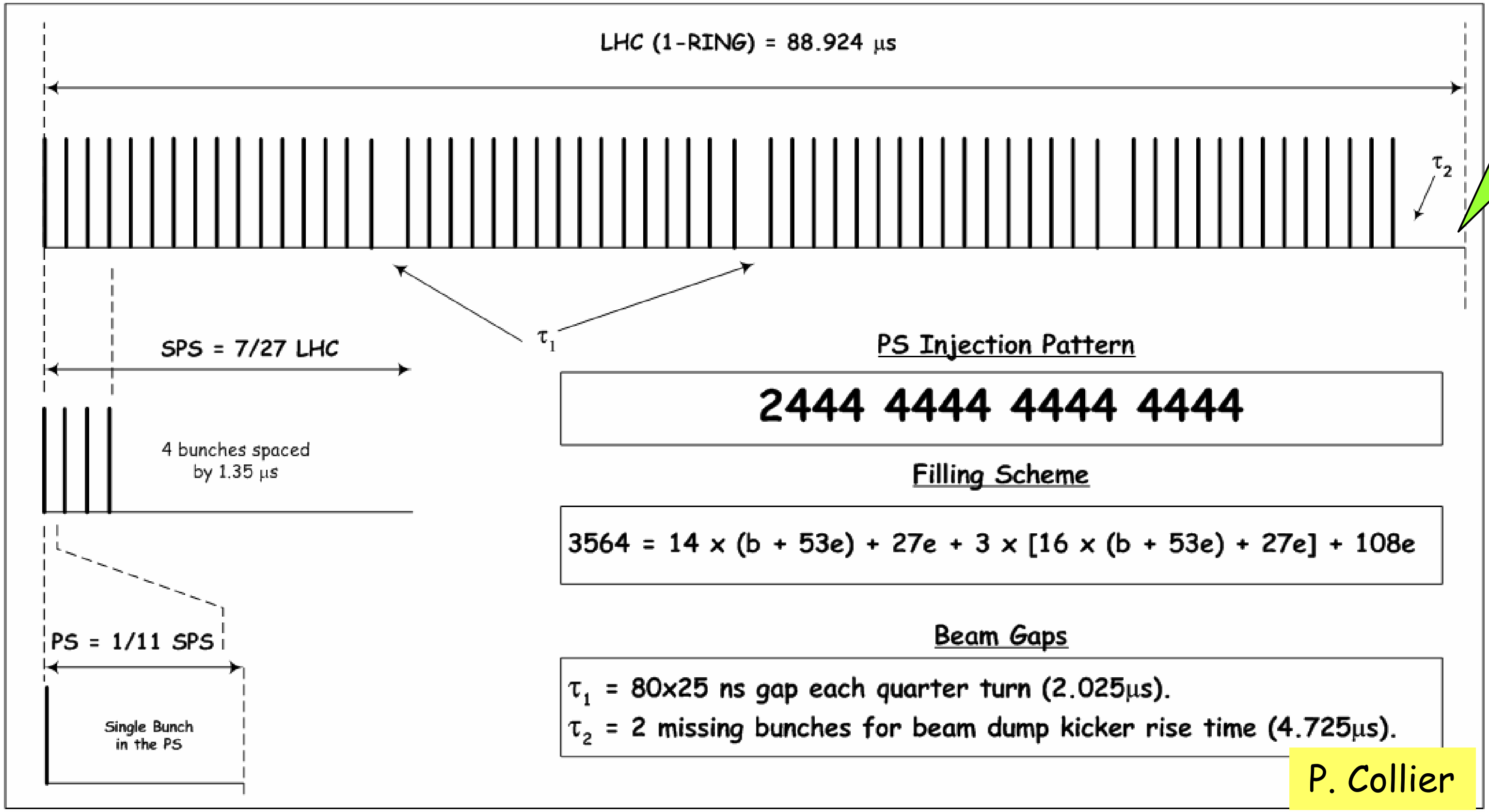


	Nb of bunches	Pb ions per LHC bunch	Harmonic number / Frequency
LEIR (2.5 10^8 Pb ions / 2.4 s)	1	2.5 10^8	1
PS at injection and acceleration	1		16
PS at extraction TT2 after stripper	1	1.2 10^8	16 + 169
SPS at injection (7.2 s flat-bot), after 2 or 4 transfers from PS	4		200 MHz
SPS at extraction, after 2 or 4 transfers from PS	4	9 10^7	200 MHz
LHC at injection, after 16 transfers from SPS	62	7 10^7	400 MHz

J.-P. Riunaud

Early Scheme: Pb Ion Pattern in PS, SPS, LHC

Initial Ion Bunch Pattern in the LHC (62-bunch scheme)



Filling of one LHC ring in 4′ (instead of 10′)

PS Injection Pattern

2444 4444 4444 4444

Filling Scheme

3564 = 14 x (b + 53e) + 27e + 3 x [16 x (b + 53e) + 27e] + 108e

Beam Gaps

τ_1 = 80x25 ns gap each quarter turn (2.025μs).
τ_2 = 2 missing bunches for beam dump kicker rise time (4.725μs).

P. Collier

Pb Collisions in LHC: Nominal + Early

Parameter	**Units**	**Nominal**	**Early Scheme**
Energy per nucleon	TeV/n	2.76	2.76
Initial Luminosity L_0	$cm^{-2}\ s^{-1}$	$1\ 10^{27}$	$5\ 10^{25}$
# bunches/bunch harmonic		592/891	62/66
Bunch spacing	ns	99.8	1350
β^*	m	0.5 (same as p)	1.0
Number of Pb ions/bunch		**$7\ 10^7$**	**$7\ 10^7$**
Transv. norm. rms emittance[1]	µm	1.5	1.5
r.m.s. beam radius at IP	µm	16 (same as p)	16
Longitudinal emittance	eVs/charge	2.5	2.5
bunch length (r.m.s.)	cm	7.5	7.5
Lumi initial decay time (2 exp.)	h	5.5	11

[1] $\varepsilon^*_{\mathbf{rms}} = (\beta\gamma)_{\mathbf{rel}}\ \sigma^2/\beta_{\mathbf{Twiss}}$

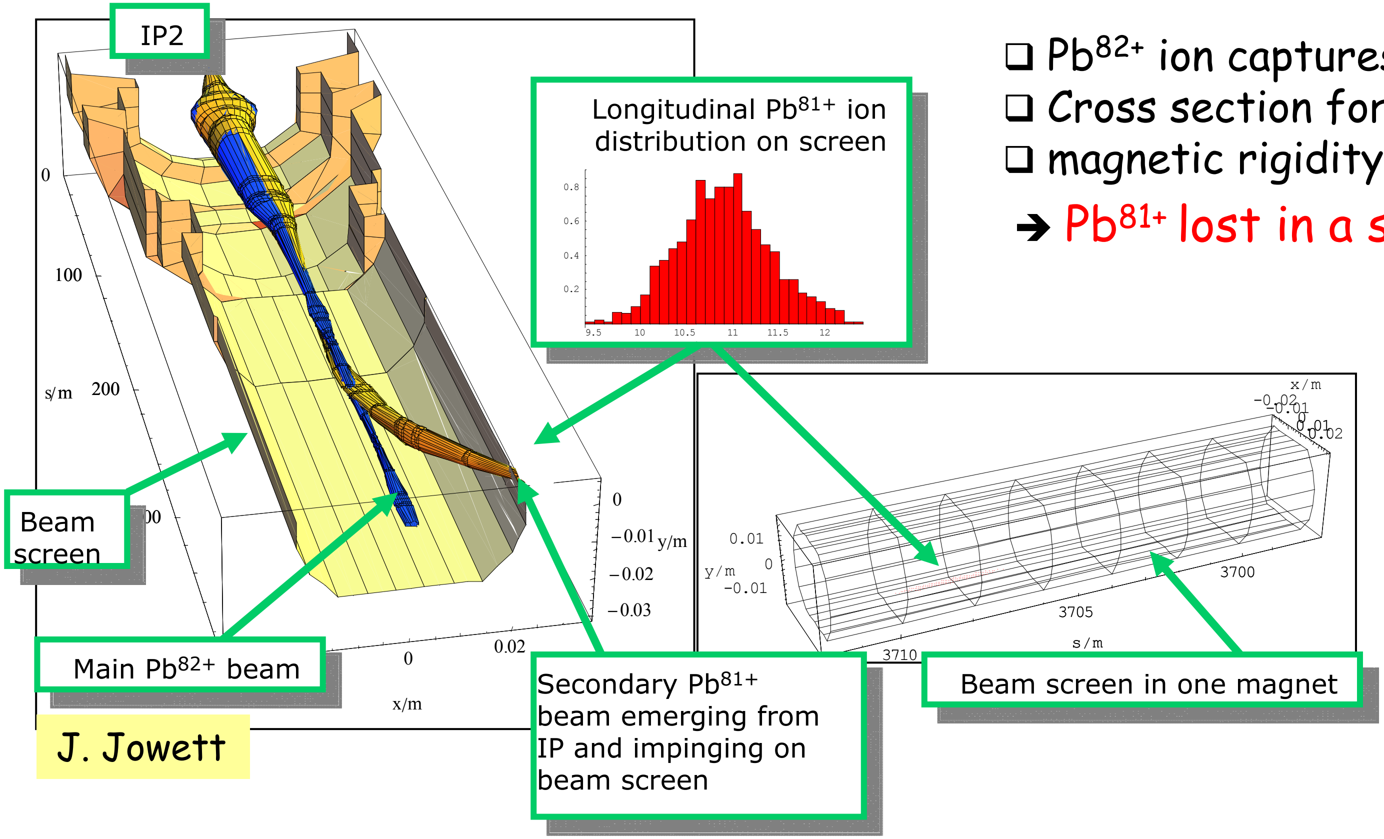
ECPP Limits LHC Ion Performance

$$^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{81+} + \mathrm{e}^{+}$$

Electron Capture from Pair Production:
interaction between colliding ion beams

- ☐ Pb^{82+} ion captures e^{-} ➔ Pb^{81+}
- ☐ Cross section for Pb ions: > 500 barn!
- ☐ magnetic rigidity ($B\rho \propto A/Q$) increases

➔ Pb^{81+} lost in a specific LHC dipole



IP2

Longitudinal Pb^{81+} ion distribution on screen

Beam screen

Main Pb^{82+} beam

Secondary Pb^{81+} beam emerging from IP and impinging on beam screen

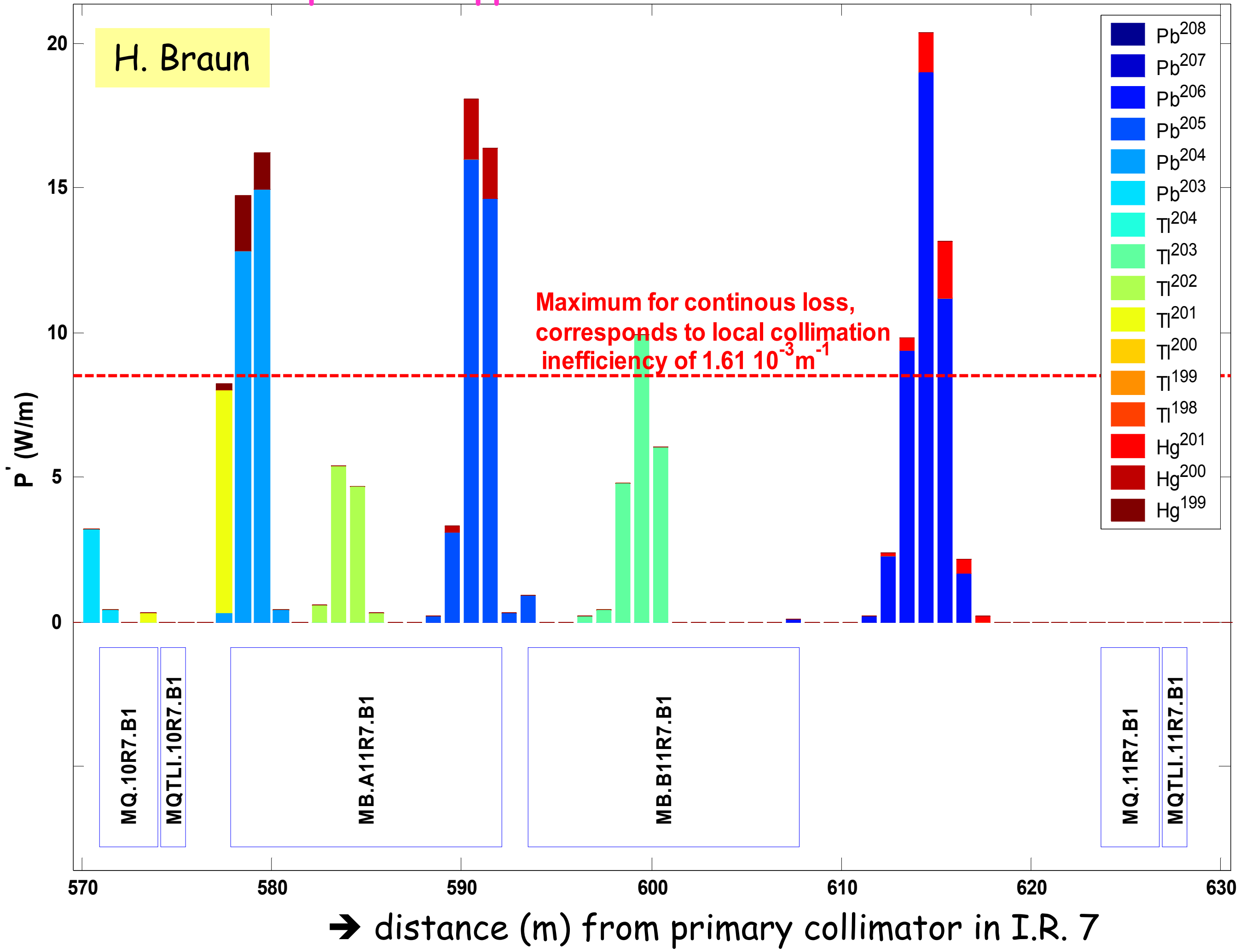
Beam screen in one magnet

J. Jowett

Do LHC Magnets Quench at Pb-Pb collisions with nominal Luminosity?

Ion Losses in the LHC with Collimator System Optimized for Protons

Heat load in LHC dispersion suppressor for a beam life-time of τ = 12 min



Maximum for continous loss, corresponds to local collimation inefficiency of 1.61 10^{-3} m^{-1}

Stored beam energy/ring (at collision):

protons	~400 MJ
Pb ion beam:	~4 MJ

BUT

Collimator system not efficient for ions

➔ excessive continuous ion loss in "dispersion suppressor" magnets

Do LHC Magnets Quench at Pb-Pb collisions with nominal Luminosity?

Summary

- ☐ The "fixed-target" Pb beam is a factor ~30 short of brightness to reach L=10^{27}cm^{-2}s^{-1}
- ☐ Phase space cooling needed to reduce emittances ➔ equip LEIR with new electron cooling
- ☐ Multiturn injection + accumulation with electron cooling provide required beam quality
- ☐ Pb ions in Linac3, LEIR, PS partially stripped ➔ UHV in LEIR, to avoid change of charge state
- ☐ Tests in 1997 with LEAR have demonstrated that LEIR will do its job
- ☐ In the PS, special gymnastics with the RF systems provide 4 ns bunches with 100 ns spacing
- ☐ In the SPS, space charge may limit Pb ion performance but is probably manageable.
- ☐ In the SPS, the ions are accelerated by the unconventional, but well tested "fixed-frequency" "variable harmonic" technique
- ☐ The nominal Pb beam may lead to LHC magnet quenches by
  - ➢ Electron Capture from Pair Production
  - ➢ Less efficient ion collimation (system optimized for protons)
- ☐ Start-up of the LHC with the "Early Beam", easier to produce, enabling studies of limiting phenomena without risk, and – above all - allowing early discoveries

Outlook

"Baseline" LHC Ion Programme: Pb-Pb collisions at 2.76 TeV/n in each beam

- Source and Linac3 commissioning until May 2005
- LEIR running in (with Early Beam) from June 2005 to March 2006
- PS/SPS ion commissioning in late 2006/early 2007 Ion beam
- In SPS and TI2, TI8, the ion running-in will obviously profit from commissioning protons (ion beam size is the same as for protons in SPS and LHC)
- Early Lead beam available for LHC in April 2008
- Nominal Lead beam planned for 2009/10 but needs more work in injectors and LHC

Not in the "Baseline" Programme:

- Pb – proton collisions (being studied, looks feasible) (2011?)
- Lighter-ion collisions (e.g. Ar-Ar, Kr-Kr, In-In): each species to be studied, optimized and commissioned through the injectors and the LHC. A lot of work, but appears feasible without major hardware additions.