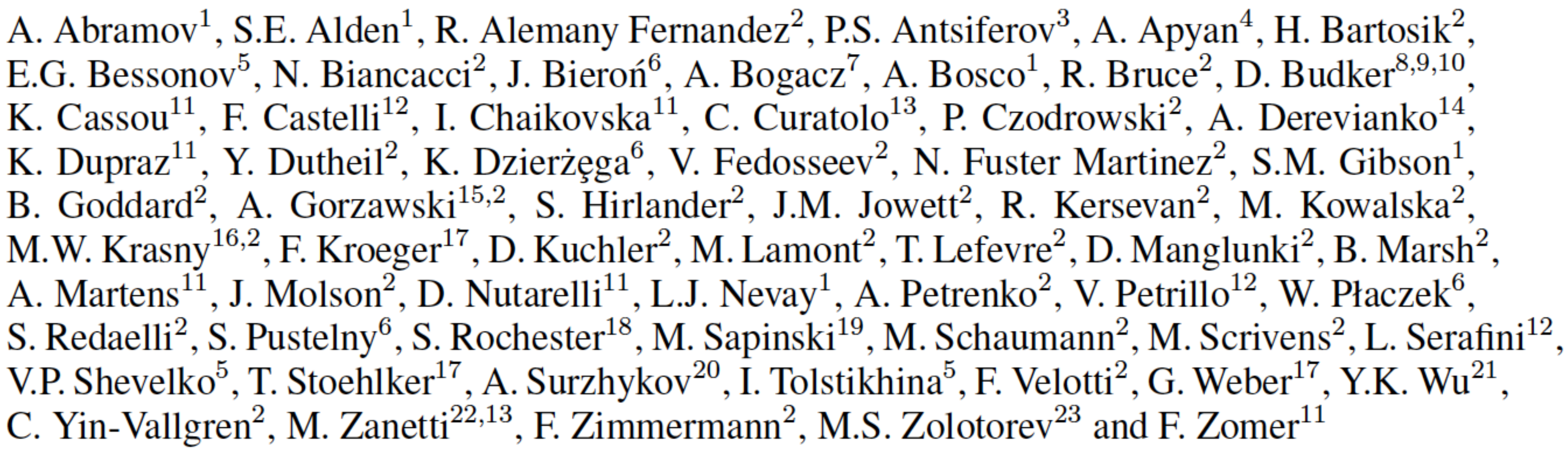
The Gamma Factory: Tools made from Light

Based on material from the following people with particular thanks to Witold Krasny



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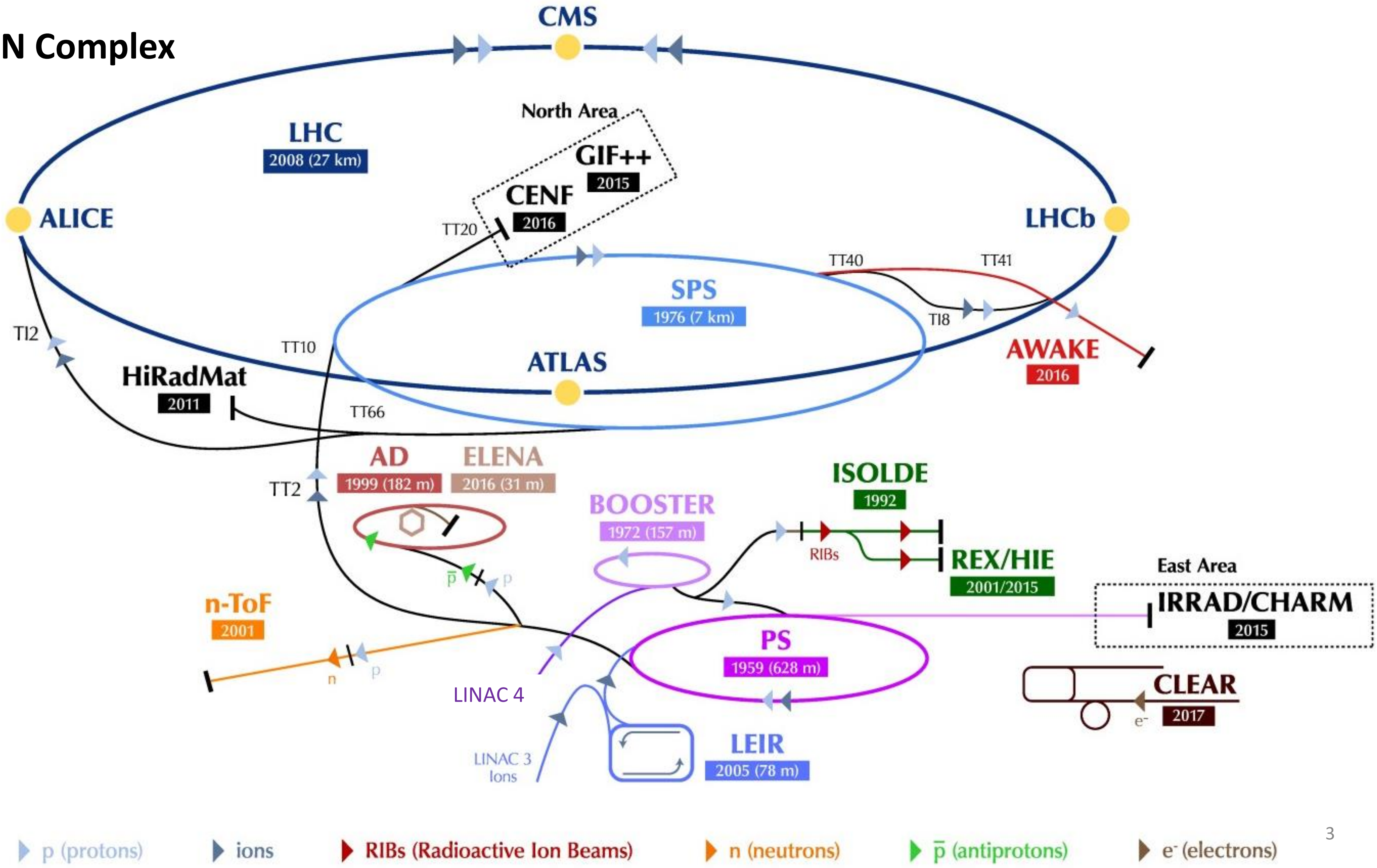
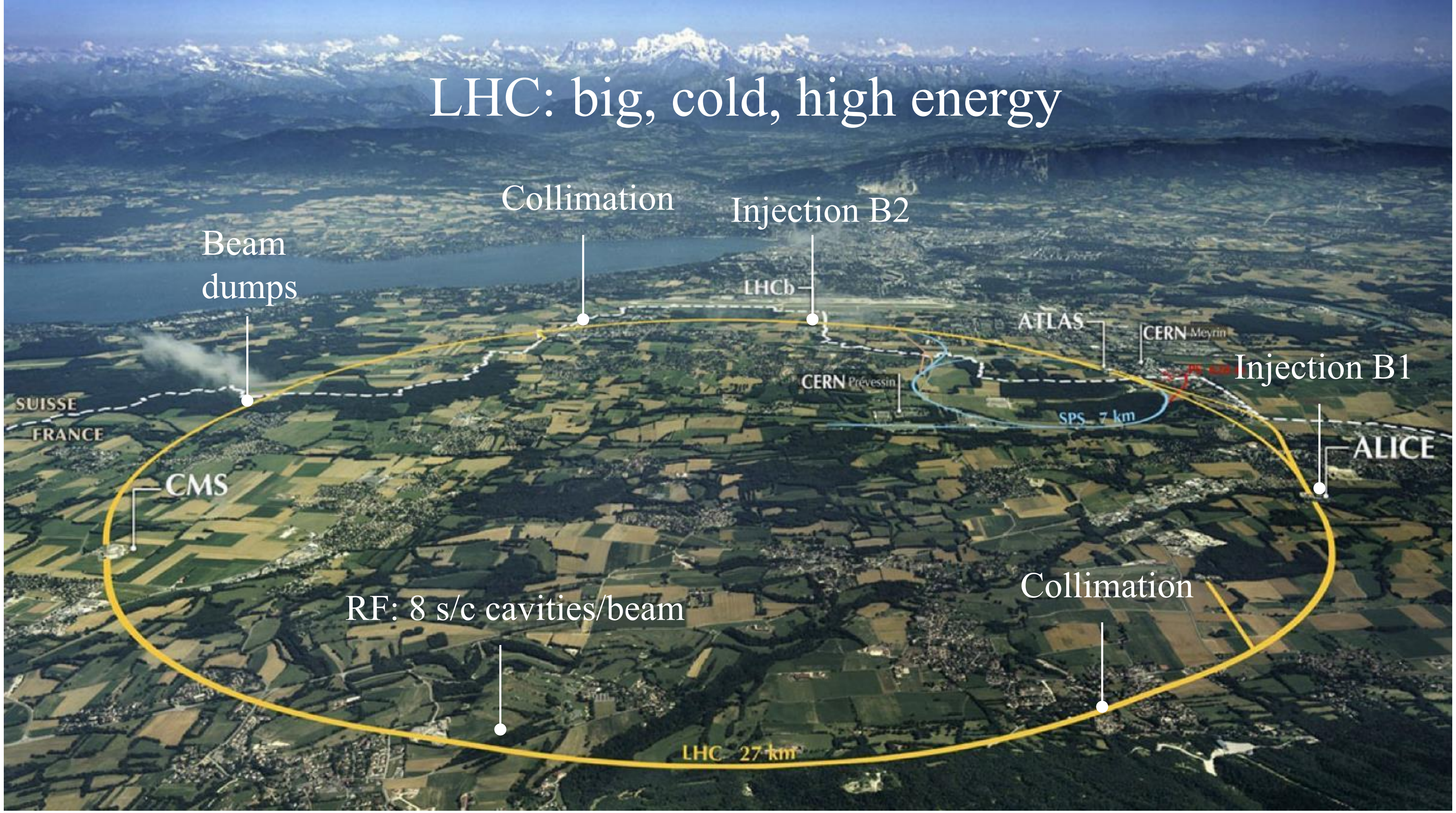
CERN Complex



LHC: big, cold, high energy



1720 Power converters
> 9000 magnetic elements
7568 Quench detection systems
1088 Beam position monitors
~4000 Beam loss monitors

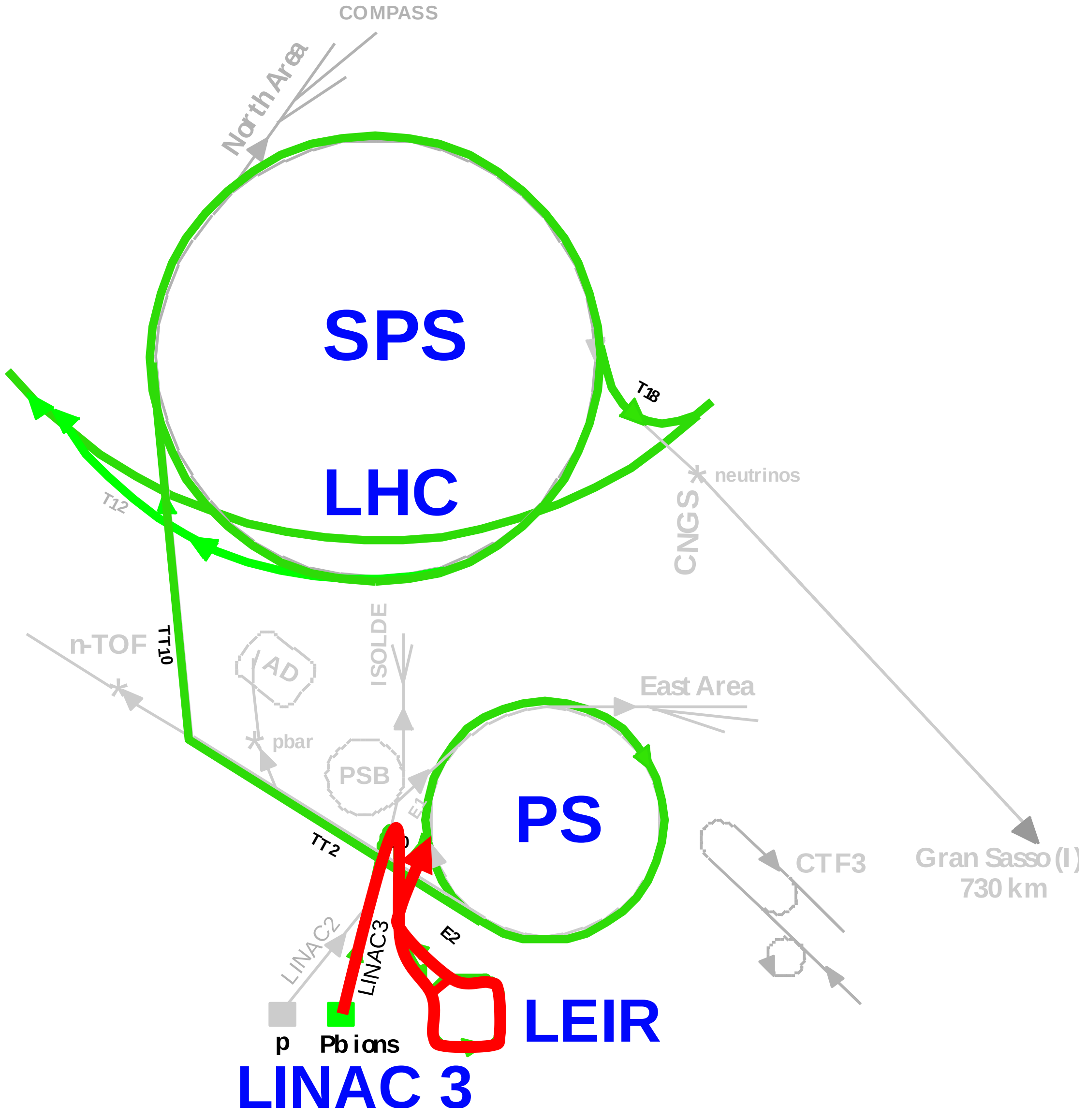
150 tonnes helium, ~90 tonnes at 1.9 K
~350 MJ stored beam energy
1.2 GJ magnetic energy per sector at 6.5 TeV

Ion production at CERN

- Electron Cyclotron Resonance (ECR) ion source (2005)
  - Provides highest possible intensity of e.g. Pb29+

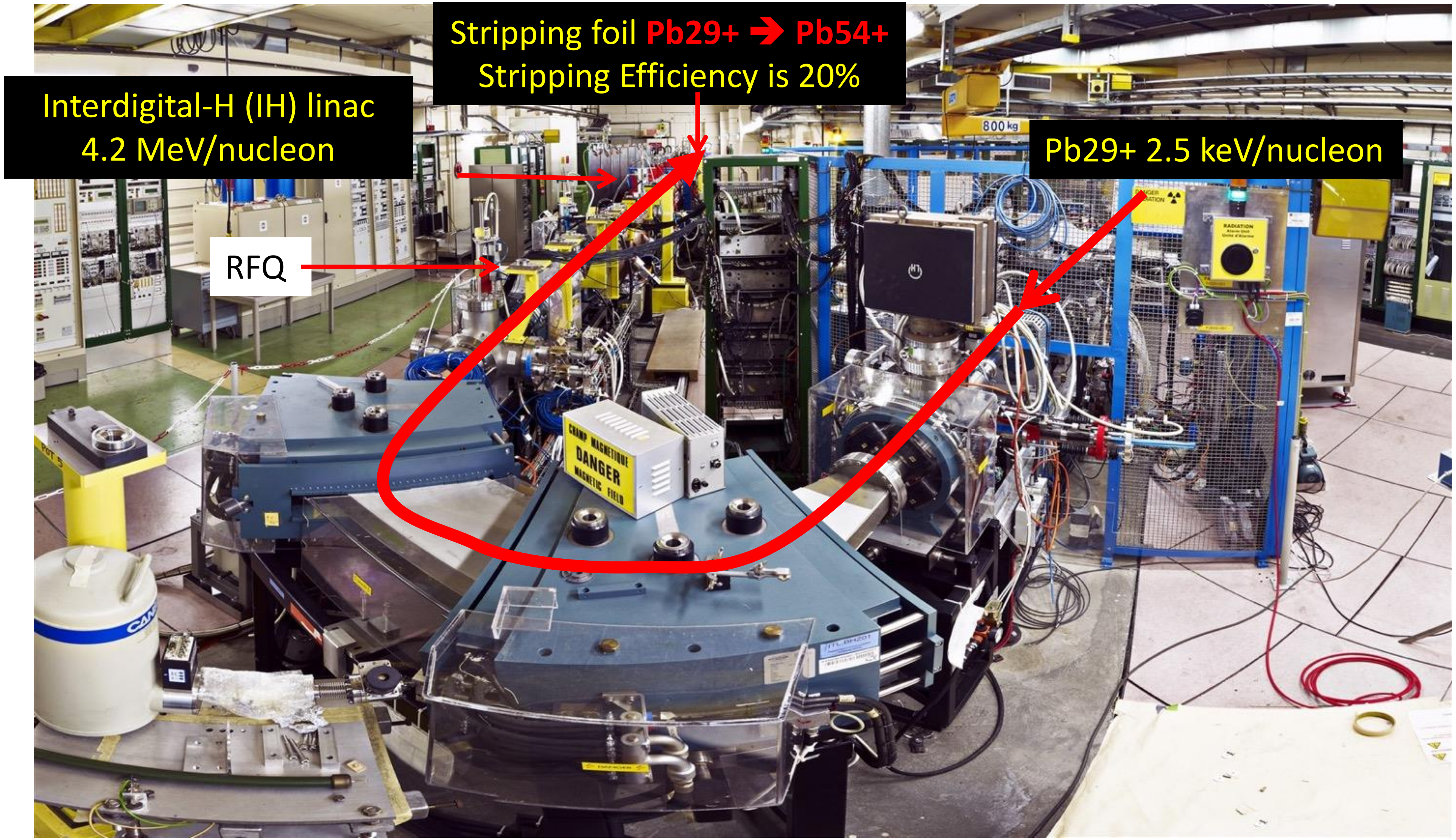
- RFQ - Linac3
  - Accelerate to LEIR injection energy
  - Strip to Pb54+

- LEIR (2005)
  - Accumulate and cool Linac3 beam
  - Prepare bunch structure for PS
  - Accelerate to PS injection energy



Main clients: NA61, LHC (ATLAS, CMS, ALICE, LHCb, LHCf)

Linac3



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

Interdigital-H (IH) linac
4.2 MeV/nucleon

RFQ

Pb29+ 2.5 keV/nucleon

Species to date

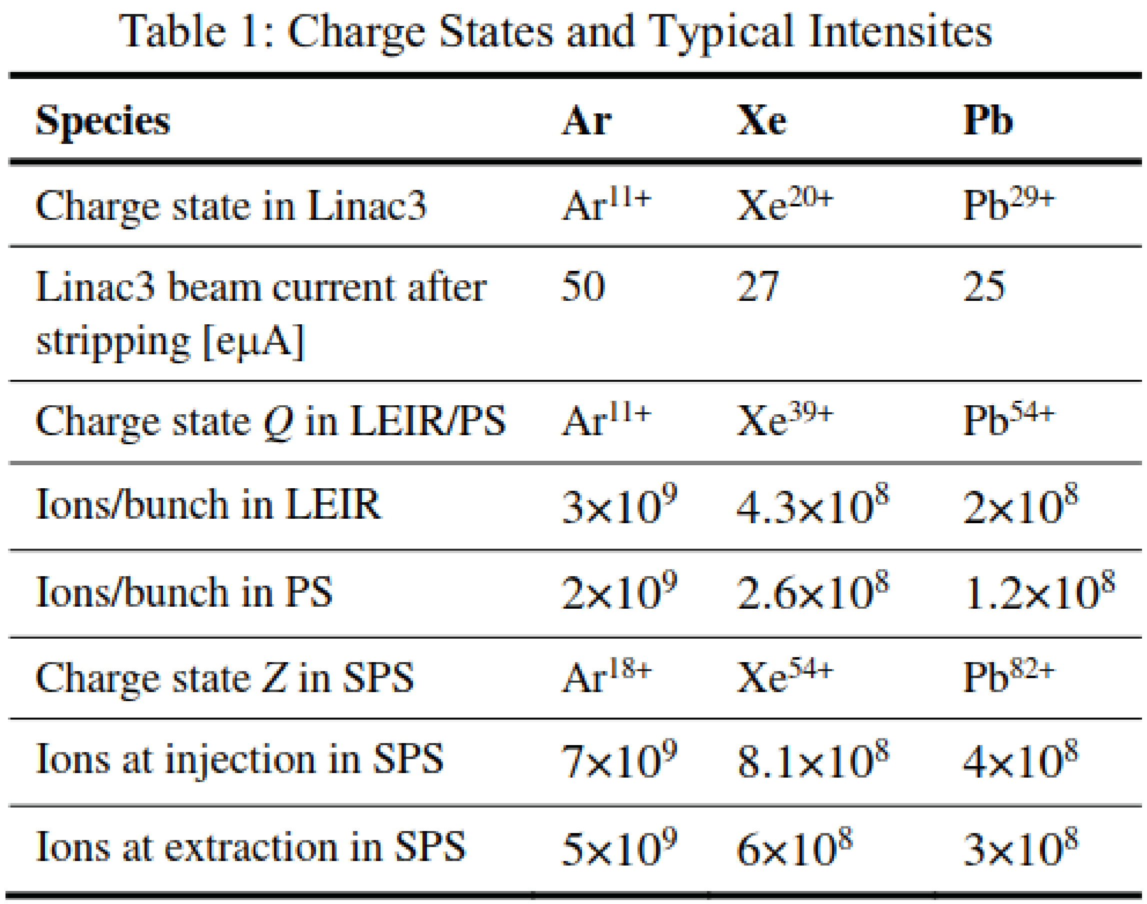


Table 1: Charge States and Typical Intensites

Species	**Ar**	**Xe**	**Pb**
Charge state in Linac3	Ar^{11+}	Xe^{20+}	Pb^{29+}
Linac3 beam current after stripping [eμA]	50	27	25
Charge state *Q* in LEIR/PS	Ar^{11+}	Xe^{39+}	Pb^{54+}
Ions/bunch in LEIR	3×10^{9}	4.3×10^{8}	2×10^{8}
Ions/bunch in PS	2×10^{9}	2.6×10^{8}	1.2×10^{8}
Charge state *Z* in SPS	Ar^{18+}	Xe^{54+}	Pb^{82+}
Ions at injection in SPS	7×10^{9}	8.1×10^{8}	4×10^{8}
Ions at extraction in SPS	5×10^{9}	6×10^{8}	3×10^{8}

Oxygen incoming

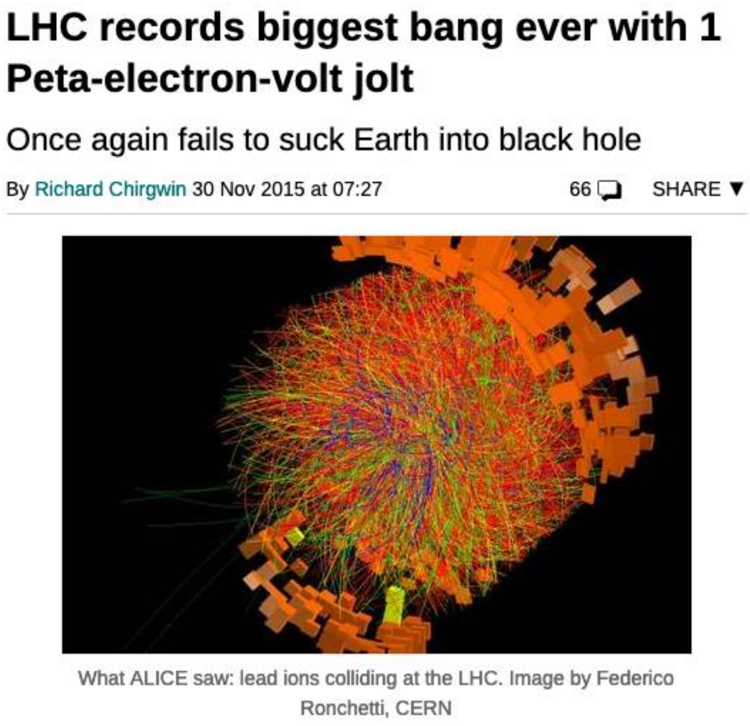
Ions in the LHC

$$\frac{\boldsymbol{p}}{Qe} = \boldsymbol{B}\rho$$

Momentum of fully stripped Pb: 7.0 **Z** TeV/c = 574 TeV

Centre of mass energy = 1.148 PeV

$$\boxed{\begin{aligned} \sqrt{s_{NN}} &= 2\sqrt{\frac{Z_1 Z_2}{A_1 A_2}}E_p \\ &= 5.02 \text{ TeV} \\ \Rightarrow E_b &= \begin{cases} 6.37Z \text{ TeV} & \text{in Pb-Pb} \\ 4\ Z \text{ TeV} & \text{in p-Pb} \\ 2.51 \text{ TeV} & \text{in p-p} \end{cases} \end{aligned}}$$



LHC records biggest bang ever with 1 Peta-electron-volt jolt

Once again fails to suck Earth into black hole

By Richard Chirgwin 30 Nov 2015 at 07:27

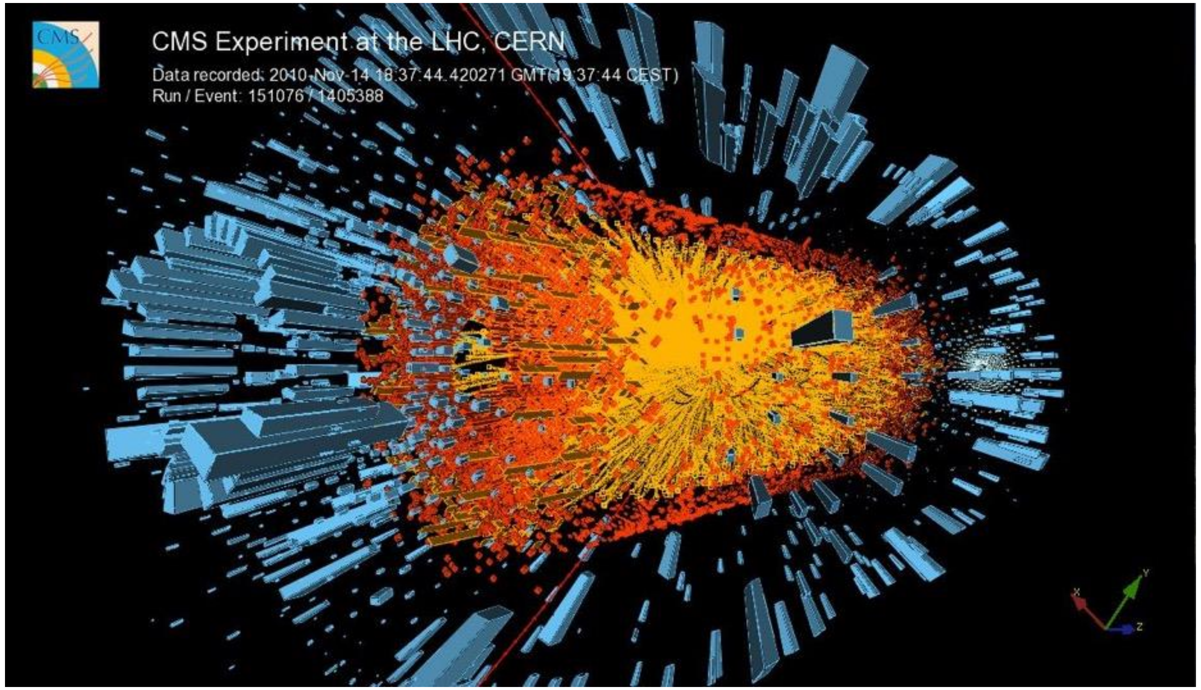
What ALICE saw: lead ions colliding at the LHC. Image by Federico Ronchetti, CERN

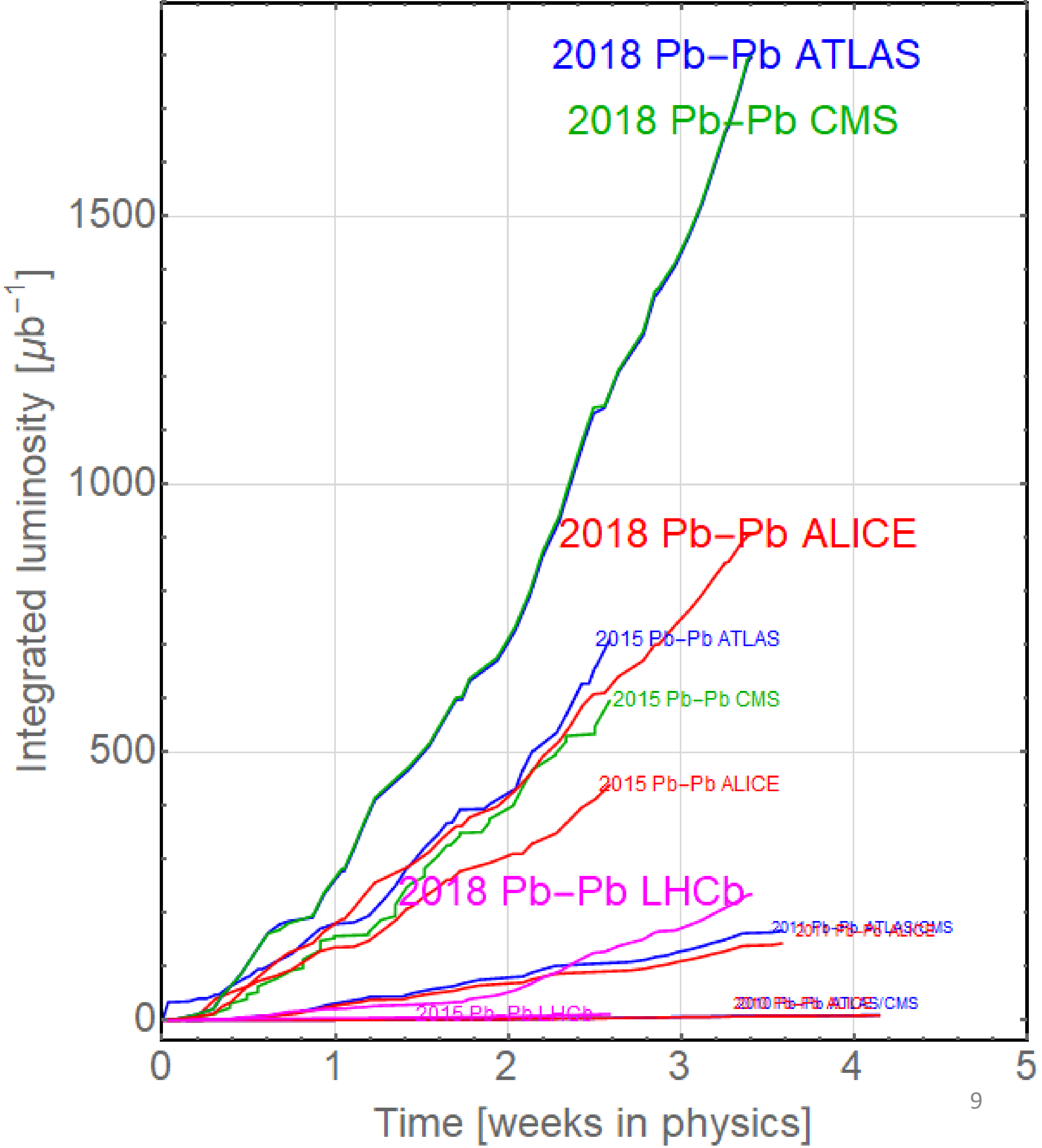
	Pb-Pb HL-LHC
β* IP1/2/5/8	0.5/0.5/0.5/1.5
E_{Pb} [Z TeV]	7
Pb/bunch[10^8]	1.8
N_b	1232
E_b [MJ]	21
L_{AA}[10^{27} cm^{-2} s^{-1}]	7

LHC Ion Program

So far:

- Lead-lead
- Proton-lead and vice versa
- Xeon-xeon (16 hours)
- Partially Stripped Ions (MD)



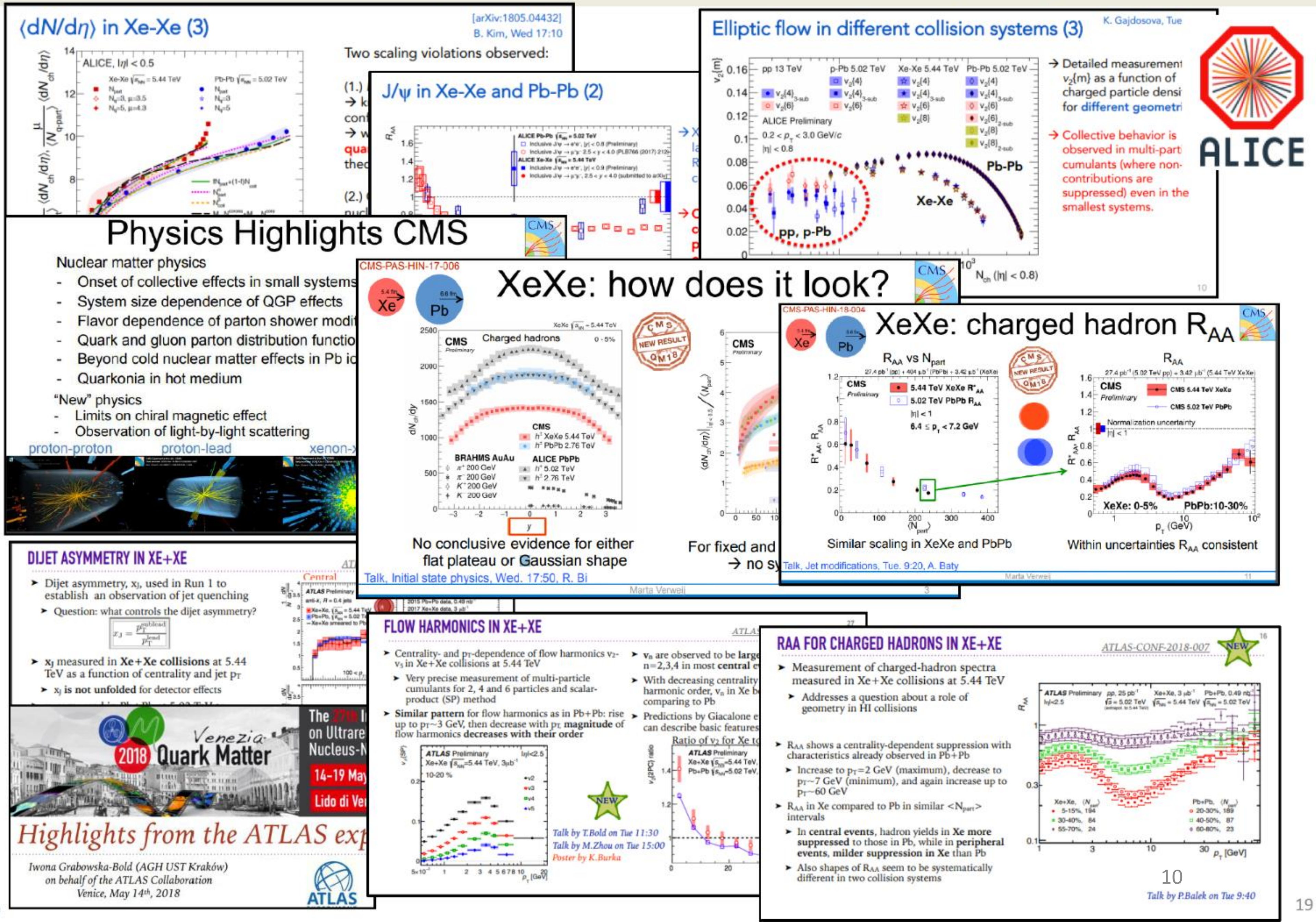


Results from Xe-Xe run of LHC at Quark Matter conference, May 2018

Rich physics harvest from 16 h (6.5 h Stable Beams) Xe-Xe run of LHC on 12/10/2017.

Results reported by all LHC experiments, clarifying the transitions between Pb-Pb, p-Pb and p-p.

Illustrates "beyond-design" potential of LHC.



⟨dN/dη⟩ in Xe-Xe (3)

[arXiv:1805.04432]
B. Kim, Wed 17:10

Two scaling violations observed:

(1.)
→ k
con
→ w
qua
thec

(2.)
nucl

J/ψ in Xe-Xe and Pb-Pb (2)

Elliptic flow in different collision systems (3)

K. Gajdosova, Tue

→ Detailed measurement v₂{m} as a function of charged particle densi for different geometri

→ Collective behavior is observed in multi-part cumulants (where non-contributions are suppressed) even in the smallest systems.

Physics Highlights CMS

Nuclear matter physics
- Onset of collective effects in small systems
- System size dependence of QGP effects
- Flavor dependence of parton shower modi
- Quark and gluon parton distribution functio
- Beyond cold nuclear matter effects in Pb i
- Quarkonia in hot medium

"New" physics
- Limits on chiral magnetic effect
- Observation of light-by-light scattering

proton-proton proton-lead xenon-

CMS-PAS-HIN-17-006

XeXe: how does it look?

No conclusive evidence for either flat plateau or Gaussian shape

For fixed and
→ no sy

Talk, Initial state physics, Wed. 17:50, R. Bi

Marta Verweij

CMS-PAS-HIN-18-004

XeXe: charged hadron R_{AA}

R_{AA} vs N_{part}

Similar scaling in XeXe and PbPb

R_{AA}

Within uncertainties R_{AA} consistent

Talk, Jet modifications, Tue. 9:20, A. Baty

Marta Verweij

DIJET ASYMMETRY IN XE+XE

- Dijet asymmetry, x_J, used in Run 1 to establish an observation of jet quenching
  - Question: what controls the dijet asymmetry?

$$x_J = \frac{p_T^{\text{sublead}}}{p_T^{\text{lead}}}$$

- x_J measured in **Xe+Xe collisions** at 5.44 TeV as a function of centrality and jet p_T
  - x_J **is not unfolded** for detector effects

Venezia 2018 Quark Matter

The 27th I on Ultrare Nucleus-N

14-19 May

Lido di Ve

Highlights from the ATLAS ex

Iwona Grabowska-Bold (AGH UST Kraków)
on behalf of the ATLAS Collaboration
Venice, May 14th, 2018

FLOW HARMONICS IN XE+XE

- Centrality- and p_T-dependence of flow harmonics v_2-v_5 in Xe+Xe collisions at 5.44 TeV
  - Very precise measurement of multi-particle cumulants for 2, 4 and 6 particles and scalar-product (SP) method
- **Similar pattern** for flow harmonics as in Pb+Pb: rise up to p_T~3 GeV, then decrease with p_T **magnitude** of flow harmonics **decreases with their order**
- v_n are observed to be **large** n=2,3,4 in most **central e**
- With decreasing centrality harmonic order, v_n in Xe b comparing to Pb
- Predictions by Giacalone e can describe basic features

Ratio of v_2 for Xe t

Talk by T.Bold on Tue 11:30
Talk by M.Zhou on Tue 15:00
Poster by K.Burka

RAA FOR CHARGED HADRONS IN XE+XE

ATLAS-CONF-2018-007

- Measurement of charged-hadron spectra measured in Xe+Xe collisions at 5.44 TeV
  - Addresses a question about a role of geometry in HI collisions
- R_{AA} shows a centrality-dependent suppression with characteristics already observed in Pb+Pb
  - Increase to p_T=2 GeV (maximum), decrease to p_T~7 GeV (minimum), and again increase up to p_T~60 GeV
- R_{AA} in Xe compared to Pb in similar $<N_{part}>$ intervals
  - In **central events**, hadron yields in **Xe more suppressed** to those in Pb, while in **peripheral events, milder suppression in Xe** than Pb
  - Also shapes of R_{AA} seem to be systematically different in two collision systems

10

Talk by P.Balek on Tue 9:40

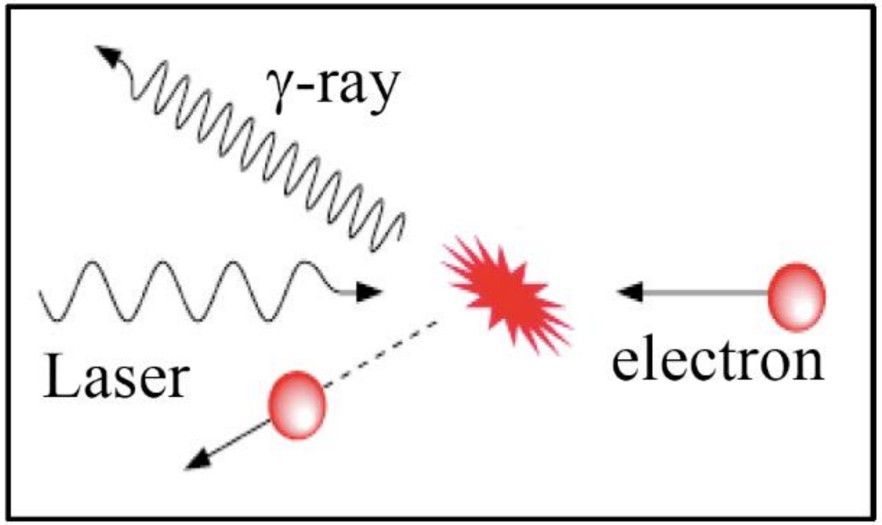
From Gamma Factory to creating Dark Matter: What happens inside the Large Hadron Collider?

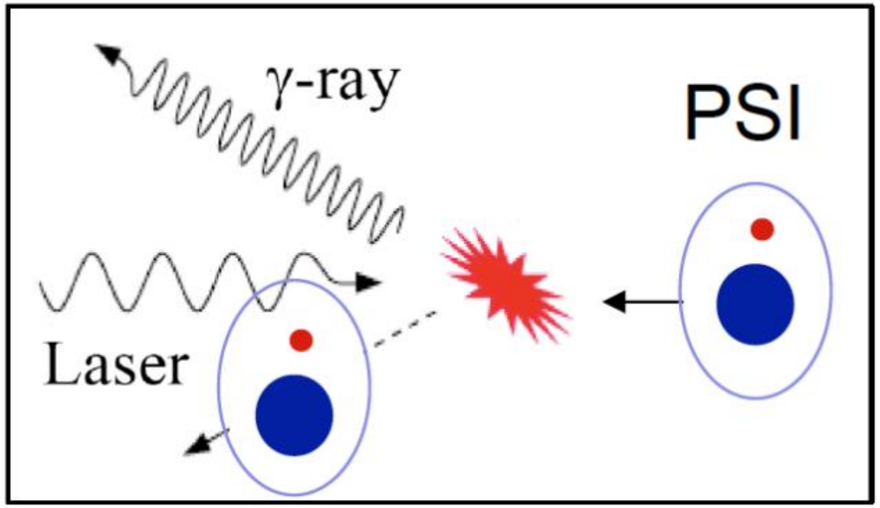
by Anthony Balchin

Gamma Factory Principles

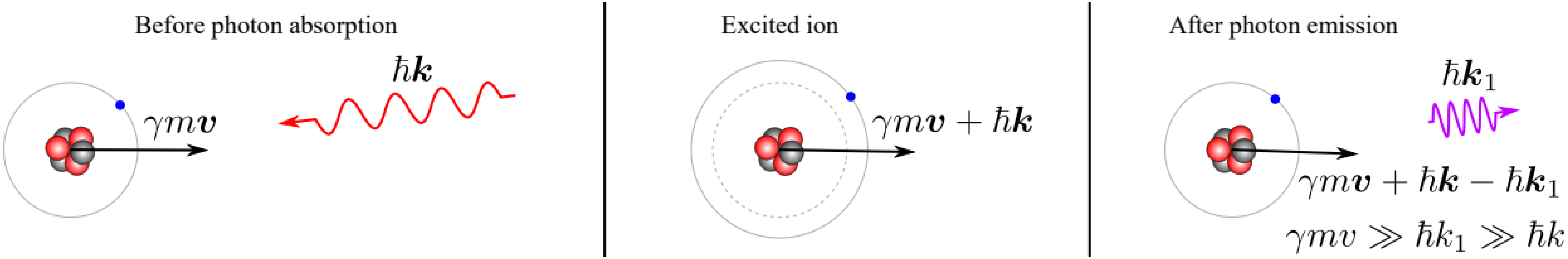
The idea

Replace an electron beam by a beam of highly ionised atoms
(Partially Stripped Ions - PSI)





Enjoy relativistic magic twice



Optical photon of angular frequency ω travelling against the PSI is boosted in the ion frame

$$\omega' = (1 + \beta)\gamma\omega \simeq 2\gamma\omega,$$

Spontaneous de-excitation of the ion produces a photon - angular distribution isotropic in the ion frame.

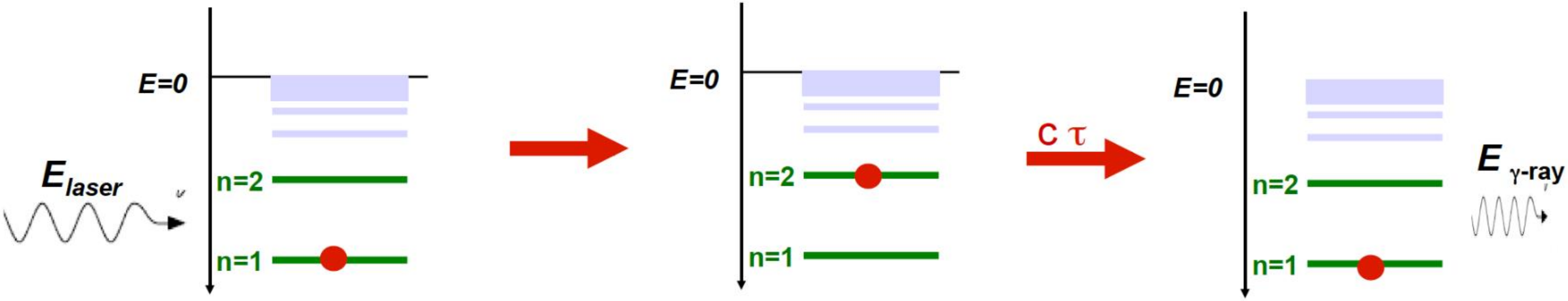
Boosting back to the lab frame:

- the emitted photons are concentrated in a small angle ≃ 1/γ in the forward direction of the ion beam.
- the angular frequency ω′′ of the photon propagating back along its incoming direction is boosted by another factor 2γ such that:

$$\omega'' \simeq 2\gamma\omega' \simeq 4\gamma^2\omega.$$

Scattering of photons on ultra-relativistic hydrogen-like, Rydberg atoms

$$-E_n = 1Ry\ Z^2/n^2$$



$$E_{laser}=1Ry\ (Z^2-Z^2/n^2)/2\gamma_L \longrightarrow E_{\gamma\text{-ray}} = E_{laser}\times 4\gamma_L^2/(1+(\gamma_L\theta)^2)$$

γ_L =E/M - Lorentz factor of the PSI beam

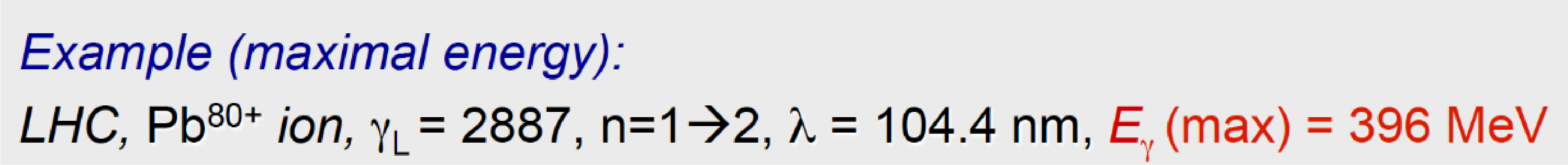
PSI beam as a frequency converter

$$\boxed{\nu^{max} = (4\,\gamma_L^2)\nu^i}$$

Can tune:

- ion type, ion charge
- atomic excitation level (transition energy and lifetime)
- beam energy
- laser type

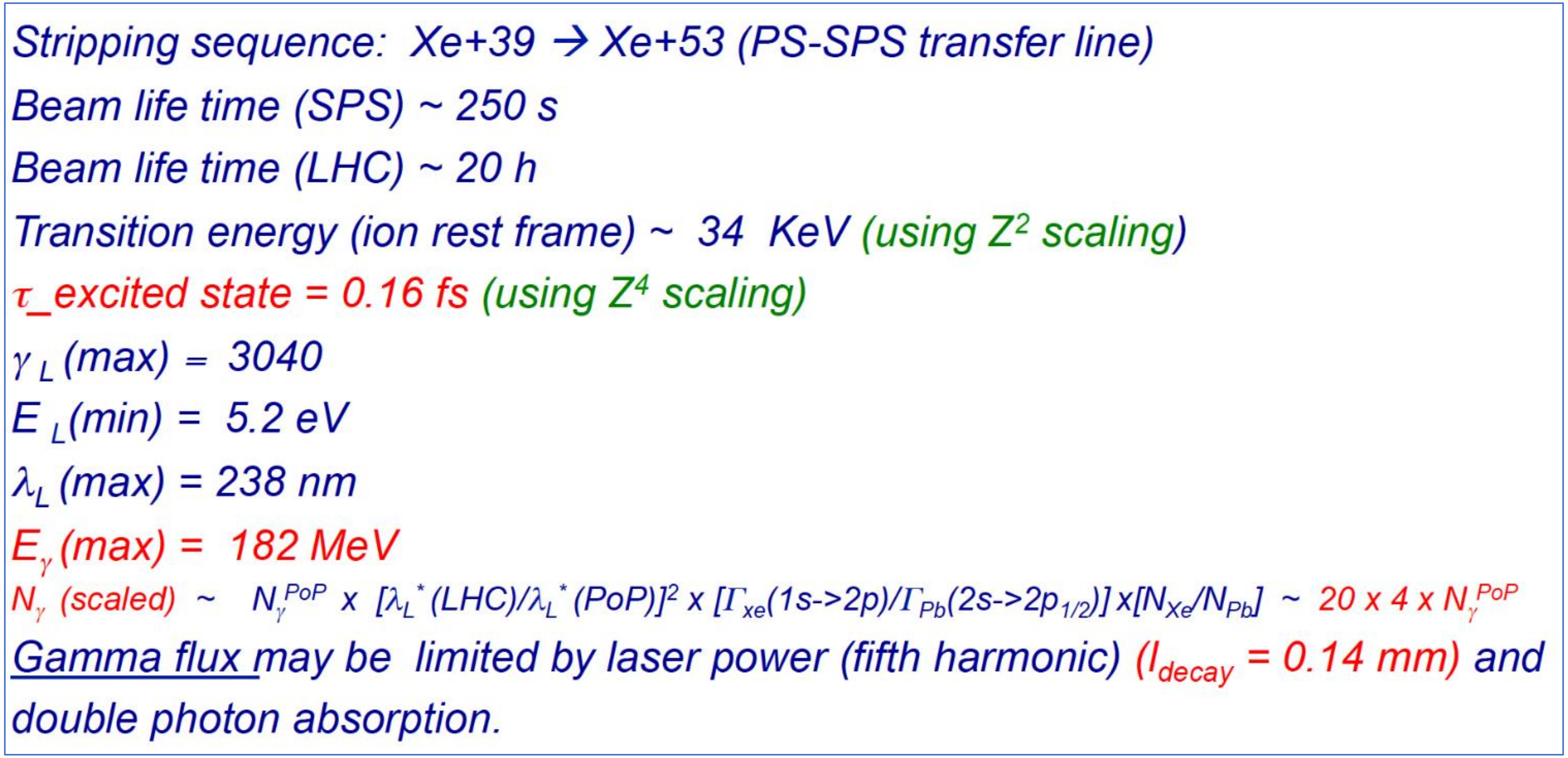
At the LHC this gives a γ-ray energy domain of **100 keV – 400 MeV**



Example (maximal energy):

LHC, Pb^{80+} *ion*, γ_L = 2887, n=1→2, λ = 104.4 nm, *E*$_\gamma$ (max) = 396 MeV

Example: H-like Xe (1s -> 2 p)$_{1/2}$



Stripping sequence: Xe+39 → Xe+53 (PS-SPS transfer line)

Beam life time (SPS) ~ 250 s

Beam life time (LHC) ~ 20 h

Transition energy (ion rest frame) ~ 34 KeV (using Z^2 scaling)

τ_excited state = 0.16 fs (using Z^4 scaling)

γ_L (max) = 3040

E_L(min) = 5.2 eV

λ_L (max) = 238 nm

E_γ (max) = 182 MeV

N_γ (scaled) ~ N_γ^{PoP} x $[\lambda_L^*(LHC)/\lambda_L^*(PoP)]^2$ x $[\Gamma_{xe}(1s\text{->}2p)/\Gamma_{Pb}(2s\text{->}2p_{1/2})]$ x$[N_{Xe}/N_{Pb}]$ ~ 20 x 4 x N_γ^{PoP}

Gamma flux may be limited by laser power (fifth harmonic) (l_{decay} = 0.14 mm) and double photon absorption.

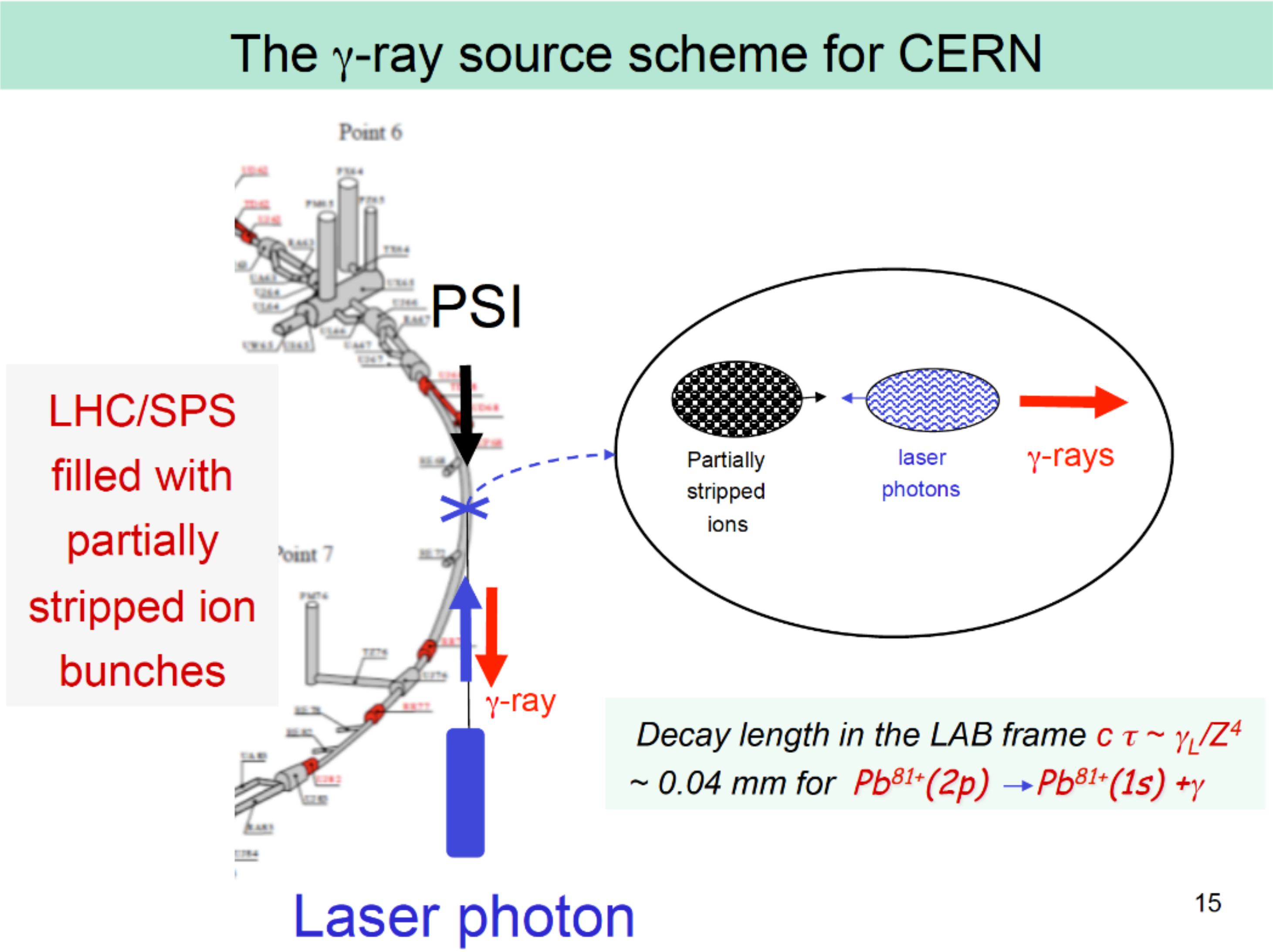
Cross-section

The cross-section for the resonant absorption of laser photons by the atomic systems is in the **giga-barn** range cf. the cross-section for electrons which is in the barn range.

→ Expect each atom to undergo ~4 excitation/de-excitations per beam/laser crossing

- As a consequence the PSI-beam-driven light source intensity could be higher than those of the electron-beam-driven facilities by a significant factor.
- For the light source working in the regime of multiple photon emissions by each of the beam ion, the photon beam intensity is expected not to be limited by the laser light intensity but by the available RF power of the ring in which partially stripped ions are stored.
- For example, the flux of up to 10^{17} photons/s could be achieved for photon energies in the 10 MeV region already with the present 16 MV circumferential voltage of the LHC cavities.

Basic ingredients for:



The γ-ray source scheme for CERN

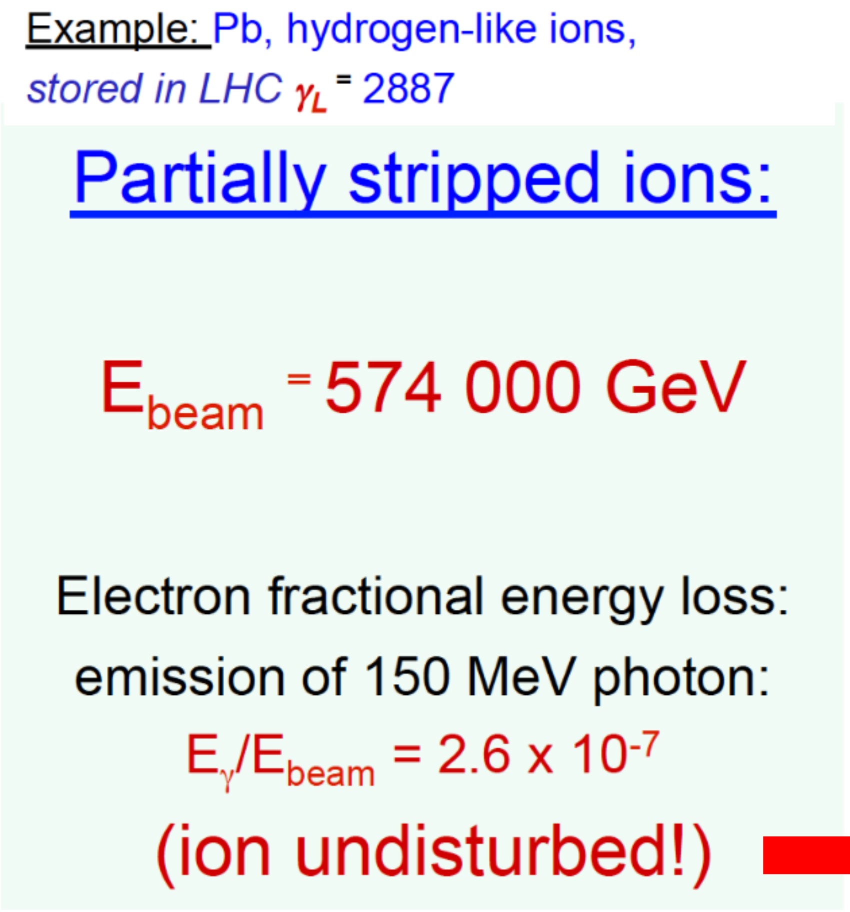
LHC/SPS filled with partially stripped ion bunches

Decay length in the LAB frame $c\,\tau \sim \gamma_L/Z^4$ ~ 0.04 mm for $Pb^{81+}(2p) \rightarrow Pb^{81+}(1s) + \gamma$

Start to worry about…!

- Beam dynamics
    - effect of energy loss/turn to photons
    - beam lifetime
    - transverse longitudinal heating/cooling
    - induced cooling
- Interaction of laser with beam at interaction point
    - momentum spread in the beam
    - wavelength, power
    - overlap
    - maintaining a high level of excitation

Energy loss



Example: Pb, hydrogen-like ions,
stored in LHC $\gamma_L = 2887$

Partially stripped ions:

$E_{beam} = 574\,000$ GeV

Electron fractional energy loss:
emission of 150 MeV photon:
$E_\gamma / E_{beam} = 2.6 \times 10^{-7}$
(ion undisturbed!)

Stable ion beam, even in the regime of multi-photon emission per turn.

The source intensity is driven by the power of the RF cavities (and sufficient ions).

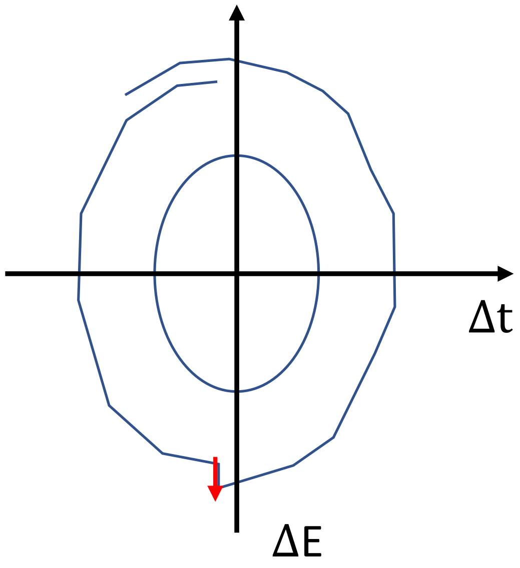
However, the effects of small losses can mount up!

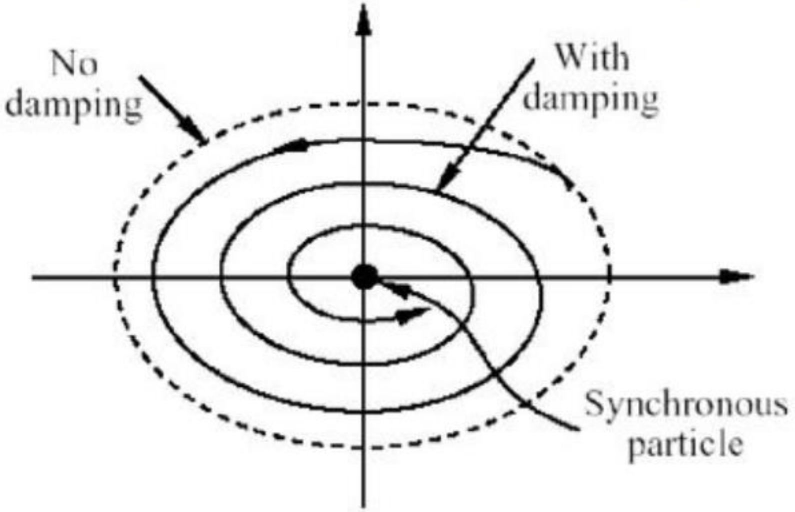
Effect of radiation on ion beam dynamics

Transverse cooling: all components of ion momentum are lost due to the photon scattering but only the longitudinal component is restored in the RF cavities.

Longitudinal heating: because energy loss per emission is stochastic

Longitudinal cooling: if energy loss grows with ion energy





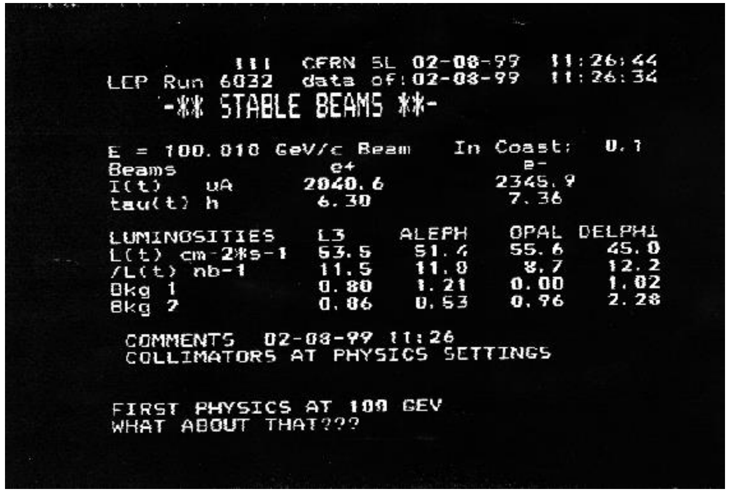
Energy loss

We have some experience from LEP: 3 GeV out of 100 GeV lost to synchrotron radiation per turn!

Beam naturally finds the appropriate stable phase at the RF cavities to compensate the energy loss (in LEP the RF system provided ~3.6 GV)

Synchrotron motion around this stable phase

Quantum emission of photons as a stochastic heating process balanced by damping due to differential energy loss



```
             111  CERN SL 02-08-99  11:26:44
LEP Run 6032  data of:02-08-99  11:26:34
    -** STABLE BEAMS **-

E = 100.010 GeV/c Beam    In Coast:  0.1
Beams              e+              e-
I(t)    uA       2040.6          2345.9
tau(t) h          6.30            7.36

LUMINOSITIES     L3     ALEPH    OPAL  DELPHI
L(t) cm-2*s-1   53.5    51.4    55.6    45.0
/L(t) nb-1      11.5    11.8     8.7    12.2
Bkg 1           0.80    1.21    0.00    1.02
Bkg 2           0.86    0.53    0.96    2.28

  COMMENTS  02-08-99 11:26
  COLLIMATORS AT PHYSICS SETTINGS


 FIRST PHYSICS AT 100 GEV
 WHAT ABOUT THAT???
```

Energy loss

GF somewhat different – single region of emission – at possibly non-dispersive location

Normally only minor energy loss/ion to synchrotron radiation – RF phase close to zero

With say ~1 GeV loss/turn – bunch will naturally find new stable phase to compensate per turn loss.

Off-momentum particles will perform synchrotron oscillations around this phase

Stochastic emission of photons could heat ensemble with possible lack of sufficient longitudinal damping depending on dU/dE

$\Delta p/p$	1.1 x 10^{-4}
RF bucket half height	3.6 x 10^{-4}

The LHC H-like Pb example:

Ion charge $Z = 81$, mass A = 208, $\boldsymbol{\gamma = 2719}$, $p_z = 526.5$ TeV/c,

$\hbar\omega' = 69$ keV (Lyman-alpha line), laser $\boldsymbol{\hbar\omega = 12}$ **eV (98 nm)**,
emitted gamma $\boldsymbol{\hbar\omega_{1,max} = 373}$ **MeV**, typical angle of emission $\boldsymbol{\theta_1 \sim 1/\gamma \sim 0.3}$ **mrad**.

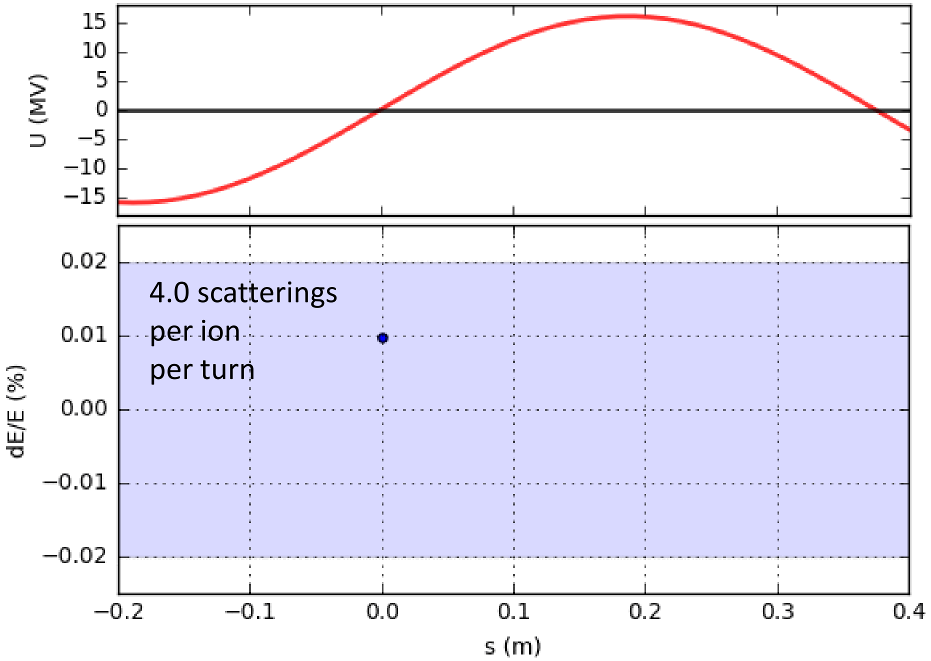
Typical transverse kick due to gamma emission:

$p_x/p_z \sim \hbar\omega'/p_z c \sim 69$ keV / 527 TeV ~ 10^{-7} mrad.

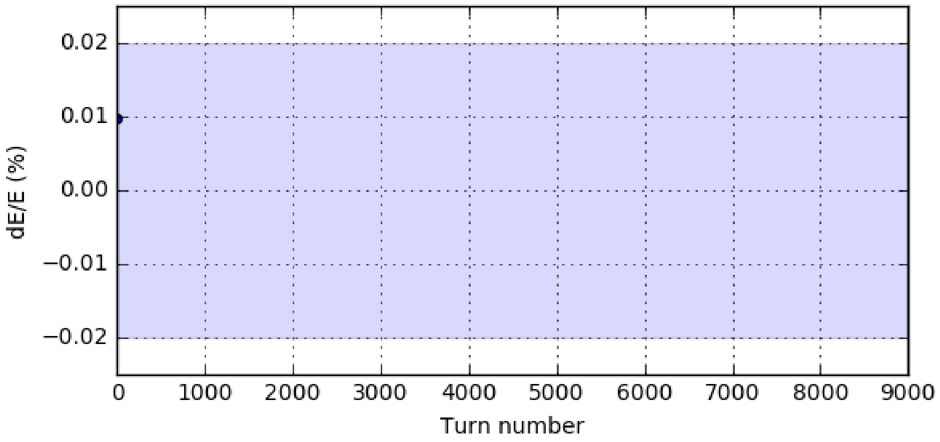
Typical transverse beam parameters at the LHC interaction point for example:
Transverse beam size = 0.026 mm, angular spread = 0.026 mrad (10^5 times higher).

Typical energy spread in the beam is $\Delta p/p \sim 10^{-4}$, while the average δp_z due to the photon emission is 200 MeV/c => $\delta p_z / p_z = 200$ MeV / 527 TeV = $3.7 \cdot 10^{-7}$ => $\Delta p/\delta p \approx 300$, and even with one scattering per turn the longitudinal effects will be significant in ~100-1000 turns.

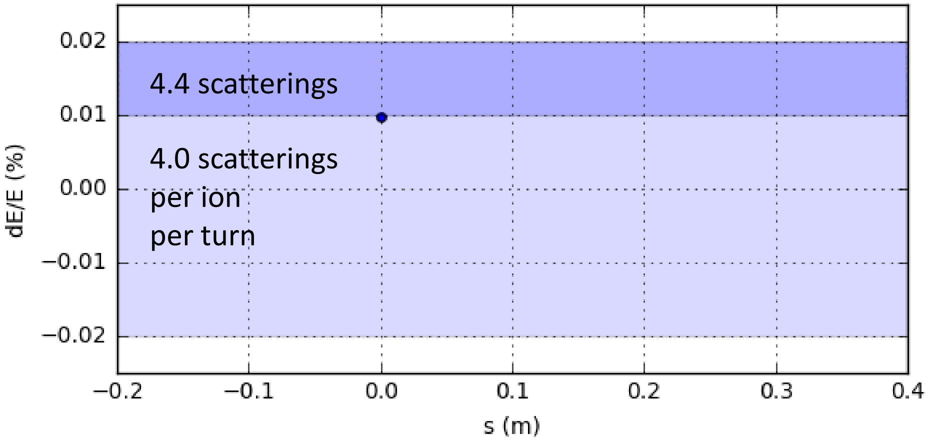
Longitudinal laser cooling is important to stabilize the ion motion:

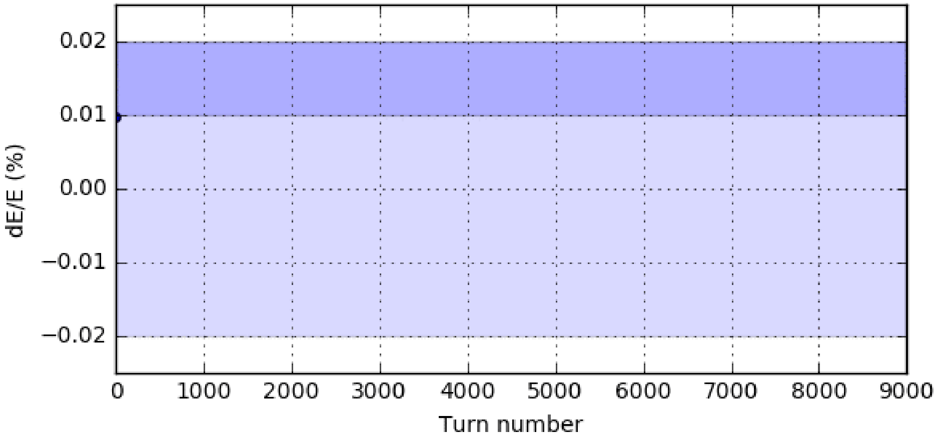


The important effect of photon emissions on ion beam dynamics is in the energy loss of the partially stripped ion. This energy loss is randomly distributed from 0 to 400 MeV in this case of Pb ion with one remaining electron in the LHC. This randomness excites uncontrolled growth of synchrotron oscillations leading to a loss of ion from the RF-bucket:



The synchrotron oscillations can be stabilized by a small change in the spectral distribution of the laser beam (or by adding another low-power laser):





Alexey Petrenko

Simulation details: http://www.inp.nsk.su/~petrenko/misc/ion_cooling/animations/

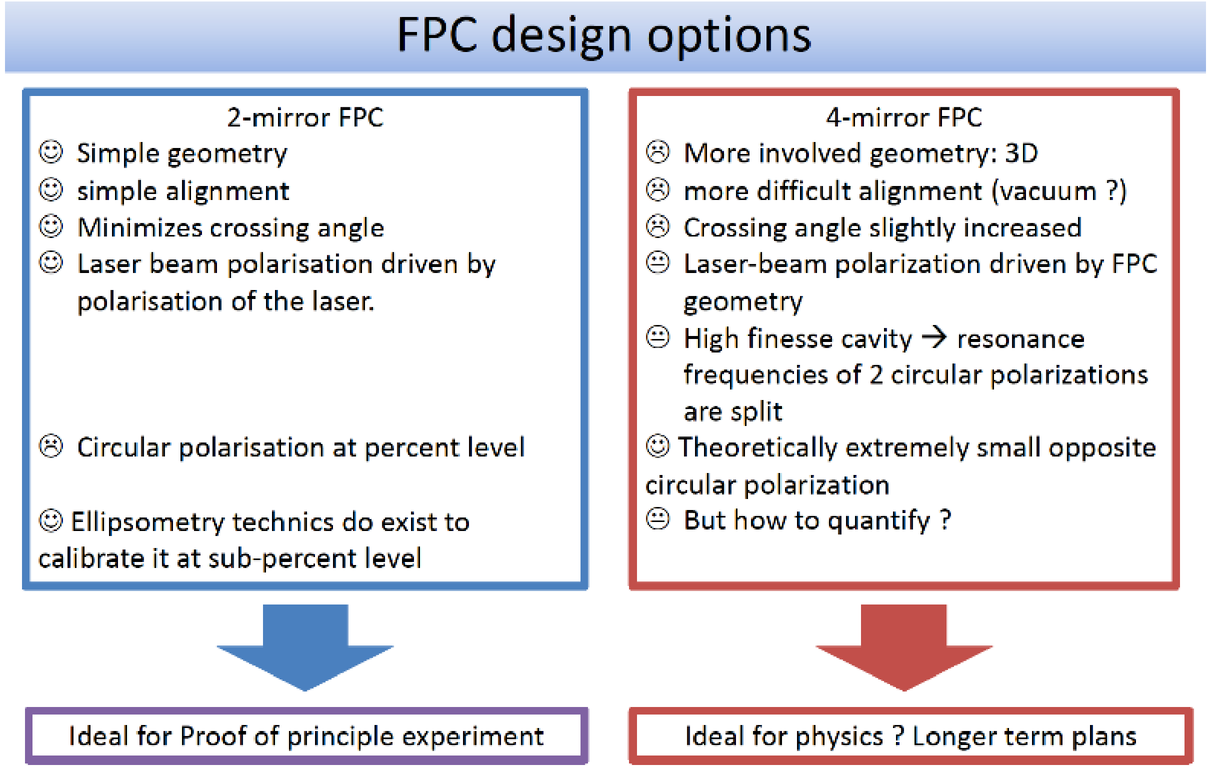
Laser

Several parameters need to be optimized:

- Laser beam transverse sizes @ the collision point
- Laser beam pulse duration
- Laser beam Spectrum
- Crossing angle

But constraints do exist and must be acounted for:

- Fabry-Perot cavity (FPC) geometry
- Laser system parameters/flexibility
- Geometrical footprint



FPC design options

2-mirror FPC

☺ Simple geometry
☺ simple alignment
☺ Minimizes crossing angle
☺ Laser beam polarisation driven by polarisation of the laser.

☹ Circular polarisation at percent level

☺ Ellipsometry technics do exist to calibrate it at sub-percent level

Ideal for Proof of principle experiment

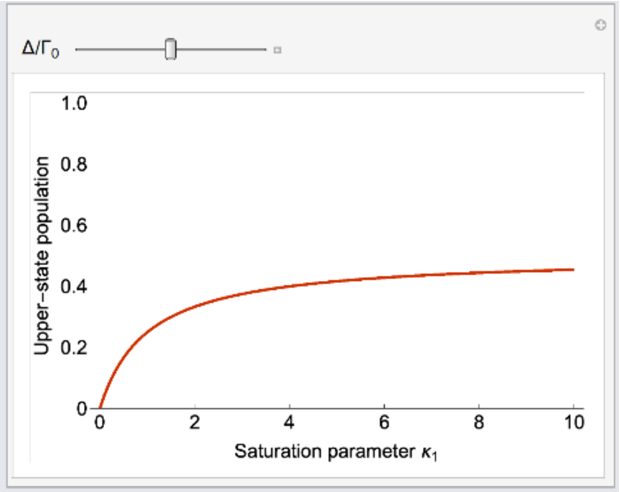
4-mirror FPC

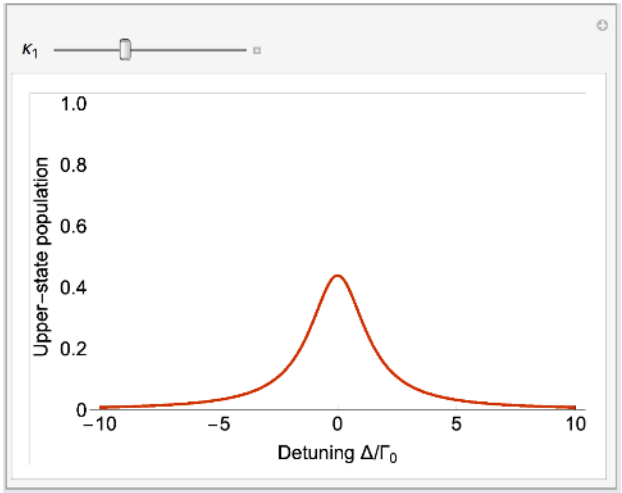
☹ More involved geometry: 3D
☹ more difficult alignment (vacuum ?)
☹ Crossing angle slightly increased
😐 Laser-beam polarization driven by FPC geometry
😐 High finesse cavity → resonance frequencies of 2 circular polarizations are split
☺ Theoretically extremely small opposite circular polarization
😐 But how to quantify ?

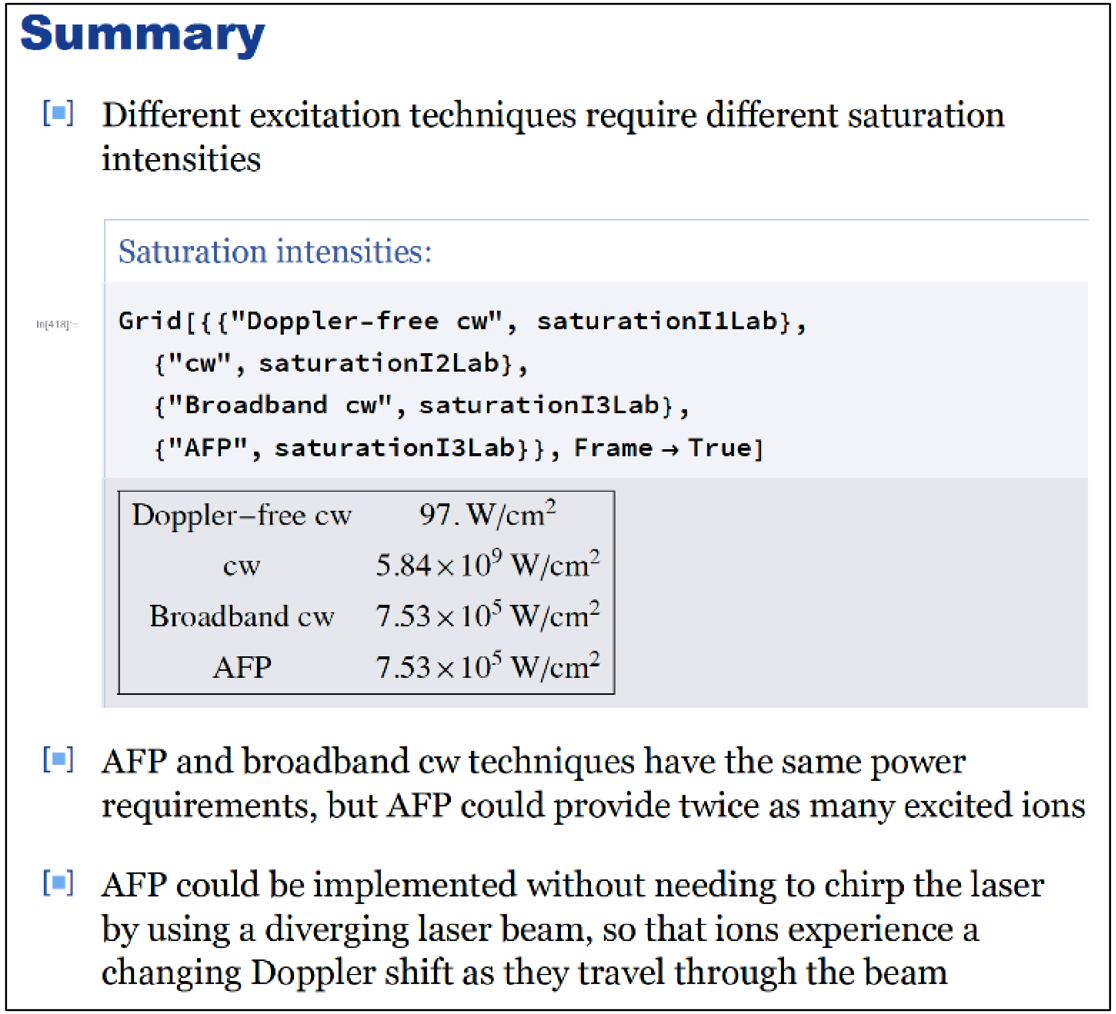
Ideal for physics ? Longer term plans

Efficient Excitation of Relativistic Ions

- Laser excitation
    - Doppler-free cw
    - cw (with Doppler broadening)
    - Broadband cw
    - Adiabatic fast passage







Summary

- Different excitation techniques require different saturation intensities

Saturation intensities:

```
Grid[{{"Doppler-free cw", saturationI1Lab},
  {"cw", saturationI2Lab},
  {"Broadband cw", saturationI3Lab},
  {"AFP", saturationI3Lab}}, Frame → True]
```

Doppler−free cw	97. W/cm^2
cw	5.84×10^9 W/cm^2
Broadband cw	7.53×10^5 W/cm^2
AFP	7.53×10^5 W/cm^2

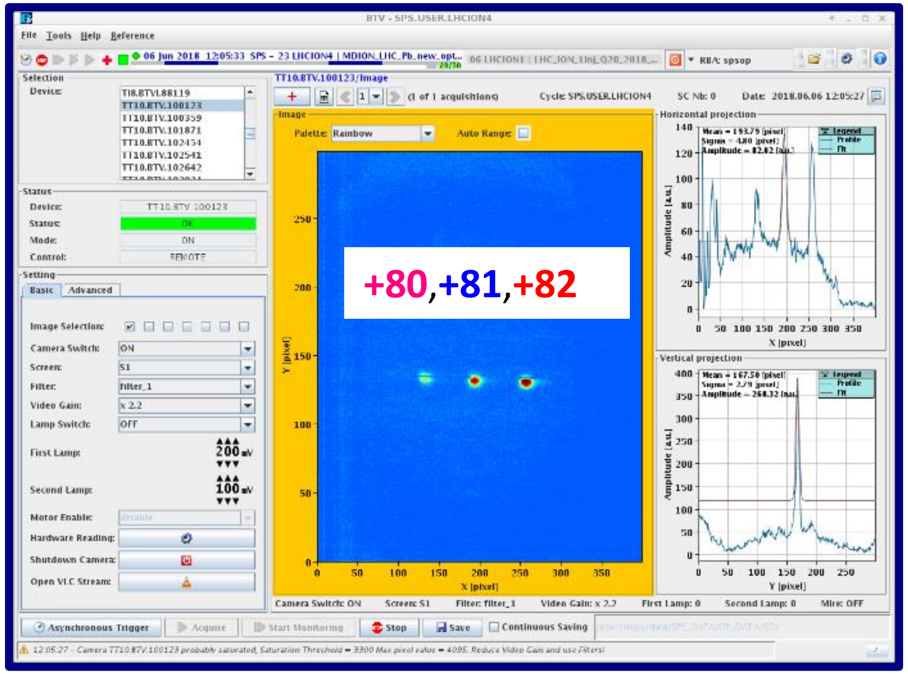
- AFP and broadband cw techniques have the same power requirements, but AFP could provide twice as many excited ions
- AFP could be implemented without needing to chirp the laser by using a diverging laser beam, so that ions experience a changing Doppler shift as they travel through the beam

Progress

"Are we there yet?"

Stripping - June 2018 Machine Development

26.01.2018
The 150μm (212μm crossed by the beam as installed at 45 degrees) thick Al foil has been installed on the FT16.BTV352 in the TT2 line!



Selection
Device: TI8.BTVI.88119, TT10.BTV.100123, TT10.BTV.100359, TT10.BTV.101871, TT10.BTV.102454, TT10.BTV.102541, TT10.BTV.102642

Status
Device: TT10.BTV.100123
Status: OK
Mode: ON
Control: REMOTE

Setting
Basic | Advanced
Image Selection: ☑ ☐ ☐ ☐ ☐ ☐ ☐
Camera Switch: ON
Screen: S1
Filter: filter_1
Video Gain: x 2.2
Lamp Switch: OFF
First Lamp: 200 mV
Second Lamp: 100 mV
Motor Enable:
Hardware Reading:
Shutdown Camera:
Open VLC Stream:

Palette: Rainbow   Auto Range: ☐

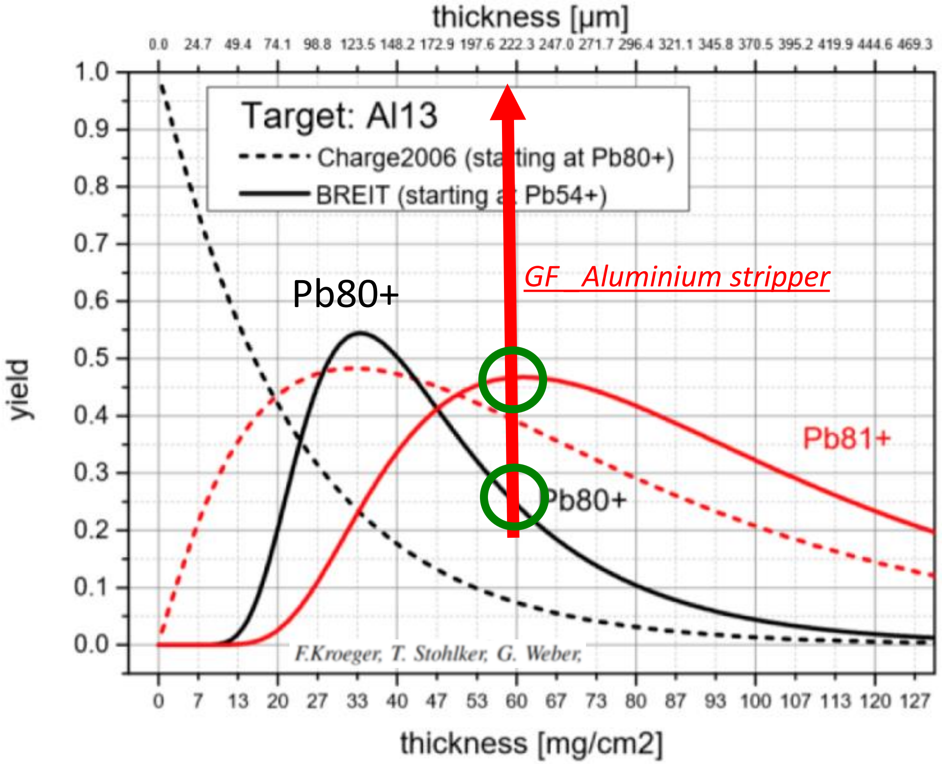
Cycle: SPS.USER.LHCION4   SC Nb: 0   Date: 2018.06.06 12:05:27

Mean = 193.79 [pixel]
Sigma = 4.80 [pixel]
Amplitude = 82.02 [a.u.]

Mean = 167.50 [pixel]
Sigma = 2.79 [pixel]
Amplitude = 268.32 [a.u.]

Camera Switch: ON   Screen: S1   Filter: filter_1   Video Gain: x 2.2   First Lamp: 0   Second Lamp: 0   Mire: OFF

12:05:27 - Camera TT10.BTV.100123 probably saturated, Saturation Threshold = 3300 Max pixel value = 4095. Reduce Video Gain and use Filters!



BCT measurements suggest:

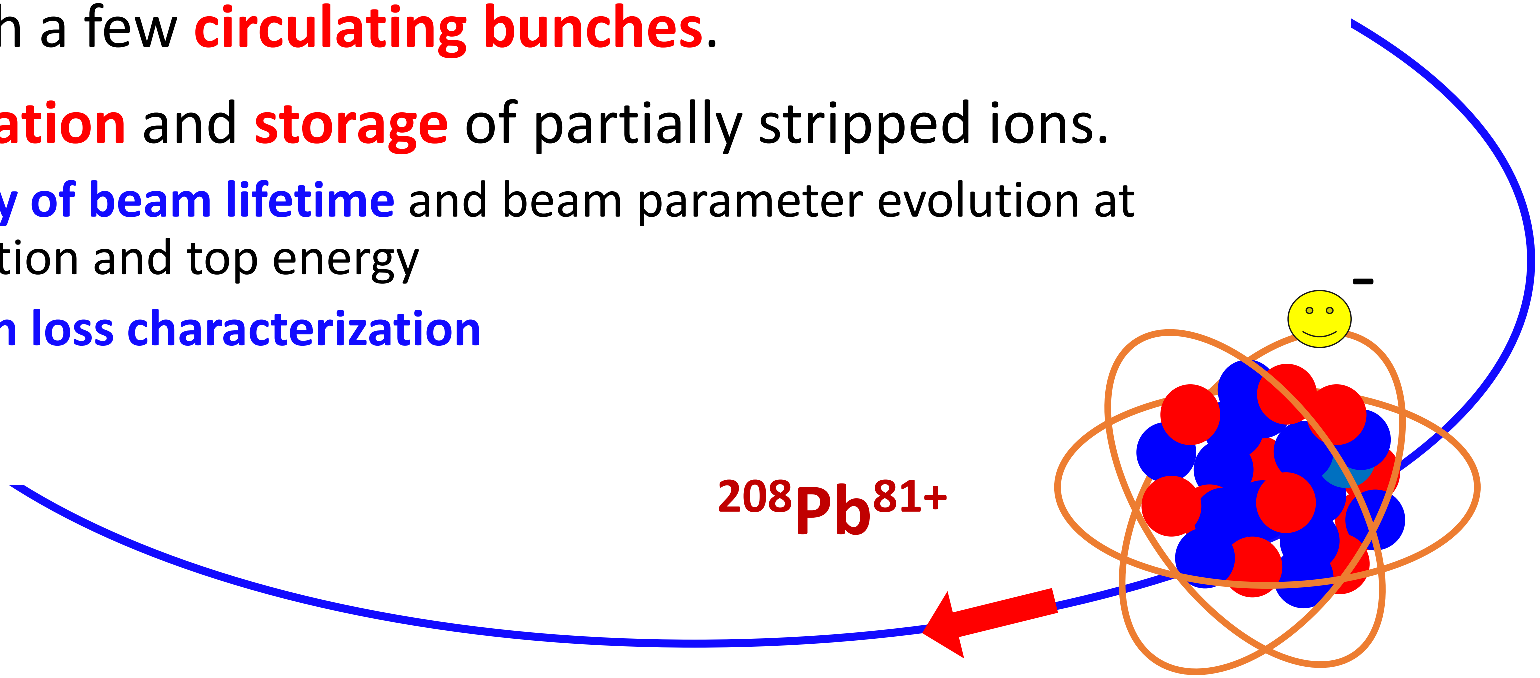
- 30% stripping efficiency for 80+
- 50% stripping efficiency for 81+

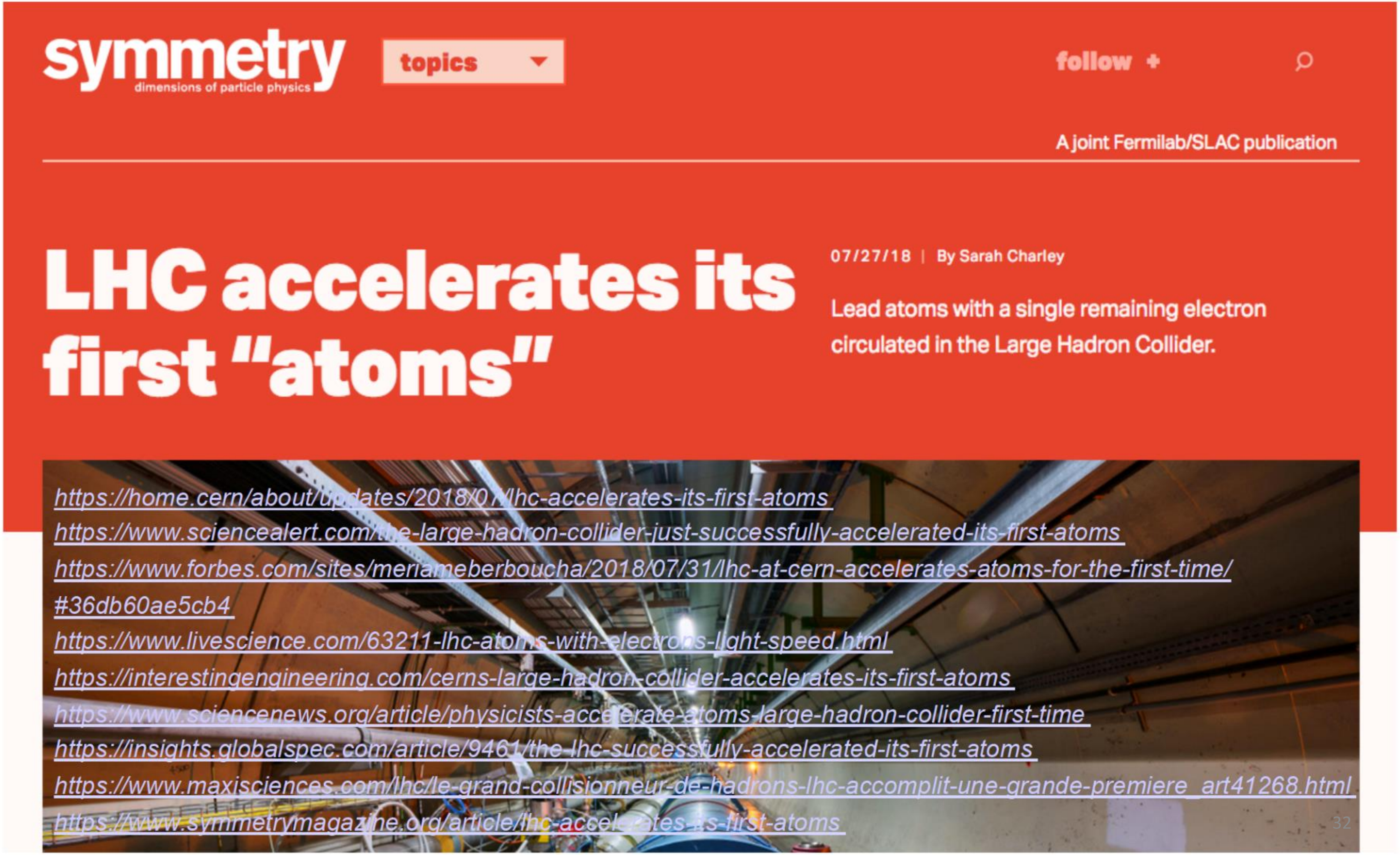
Pb80+ Pb81+

Goals of initial test in the LHC

12 hours LHC Machine Development (MD) time on 25.07.2018

- **Inject** new particle “species” in the LHC
  - Well-known Pb-208, but with one remaining electron
- Establish a few **circulating bunches**.
- **Acceleration** and **storage** of partially stripped ions.
  - ➢ **Study of beam lifetime** and beam parameter evolution at injection and top energy
  - ➢ **Beam loss characterization**





A joint Fermilab/SLAC publication

LHC accelerates its first “atoms”

07/27/18 | By Sarah Charley

Lead atoms with a single remaining electron circulated in the Large Hadron Collider.

https://home.cern/about/updates/2018/07/lhc-accelerates-its-first-atoms

https://www.sciencealert.com/the-large-hadron-collider-just-successfully-accelerated-its-first-atoms

https://www.forbes.com/sites/meriameberboucha/2018/07/31/lhc-at-cern-accelerates-atoms-for-the-first-time/#36db60ae5cb4

https://www.livescience.com/63211-lhc-atoms-with-electrons-light-speed.html

https://interestingengineering.com/cerns-large-hadron-collider-accelerates-its-first-atoms

https://www.sciencenews.org/article/physicists-accelerate-atoms-large-hadron-collider-first-time

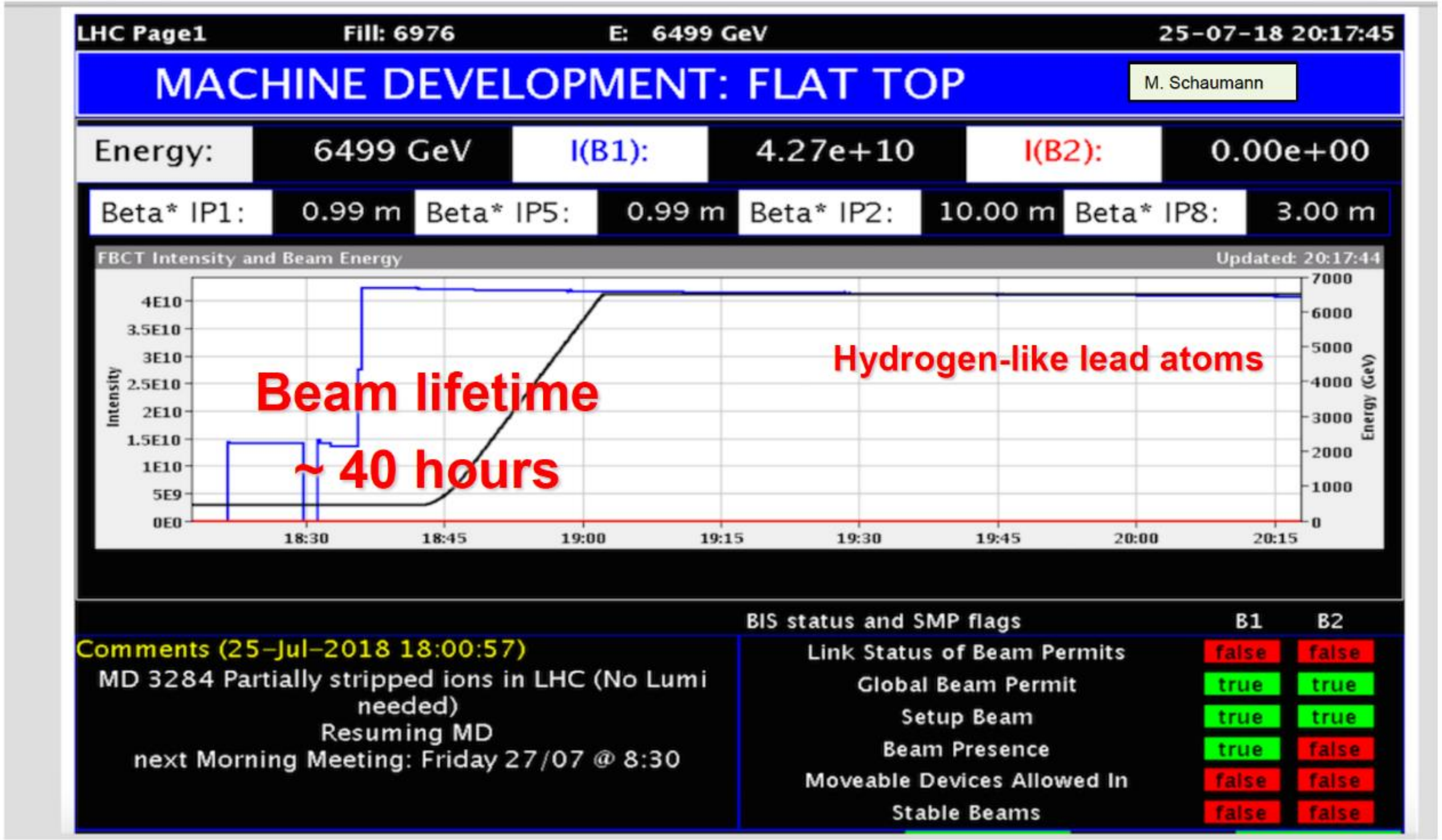
https://insights.globalspec.com/article/9461/the-lhc-successfully-accelerated-its-first-atoms

https://www.maxisciences.com/lhc/le-grand-collisionneur-de-hadrons-lhc-accomplit-une-grande-premiere_art41268.html

https://www.symmetrymagazine.org/article/lhc-accelerates-its-first-atoms

Results

2018 highlight: Successful production, injection, ramp and storage of the **hydrogen-like lead beam in LHC!**



LHC Page1 Fill: 6976 E: 6499 GeV 25-07-18 20:17:45

MACHINE DEVELOPMENT: FLAT TOP

M. Schaumann

Energy:	6499 GeV	I(B1):	4.27e+10	I(B2):	0.00e+00

Beta* IP1:	0.99 m	Beta* IP5:	0.99 m	Beta* IP2:	10.00 m	Beta* IP8:	3.00 m

Comments (25-Jul-2018 18:00:57)
MD 3284 Partially stripped ions in LHC (No Lumi needed)
Resuming MD
next Morning Meeting: Friday 27/07 @ 8:30

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	false	false
Global Beam Permit	true	true
Setup Beam	true	true
Beam Presence	true	false
Moveable Devices Allowed In	false	false
Stable Beams	false	false

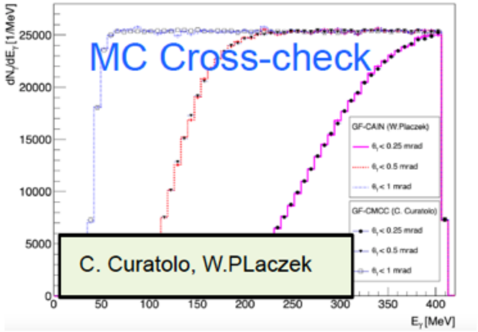
- *Intensity/bunch (~7 x 10^9 charges), 6 bunches circulating.*

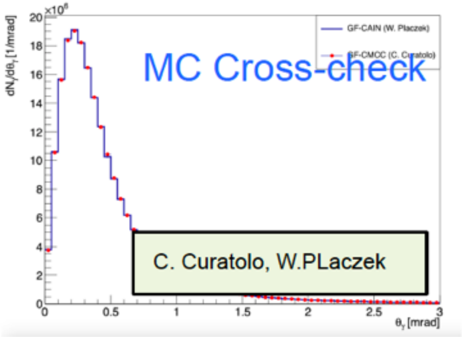
Results

- Lifetime of Pb81+ beams have been studied in LHC at 450 GeV and 6.5 TeV proton equivalent energy.
- Main observations:
  - dominant limit of the beam intensity is the collimation efficiency
  - as expected, e.g. from IBS, lifetime decreases with intensity
- Lifetime decreases with storage time
  - Average lifetime at Injection: ~20h
  - Average lifetime at Flat top: ~50h
- Preliminary beam dynamic simulations including IBS, radiation damping and debunching showed promising results but more studies needed.

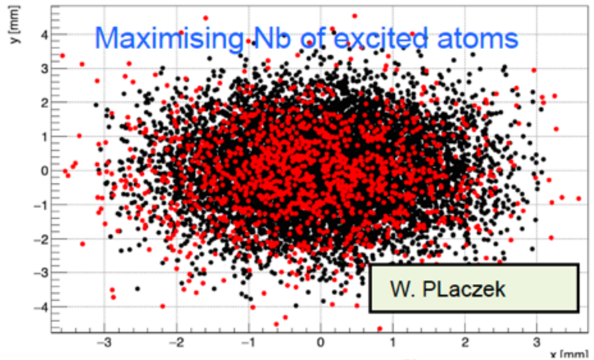
Other ongoing studies

Alexey,Wiesiek, Camilla, Aurelien, Sibahn, Slava, Inga, Felix,

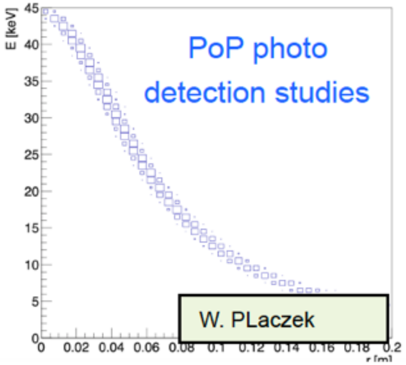




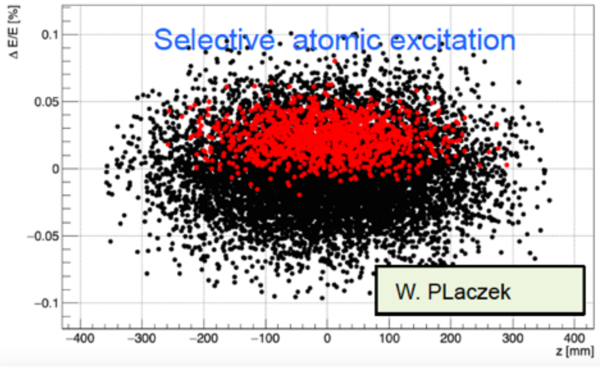
Gamma Factory: Pb^{79+} beam profile



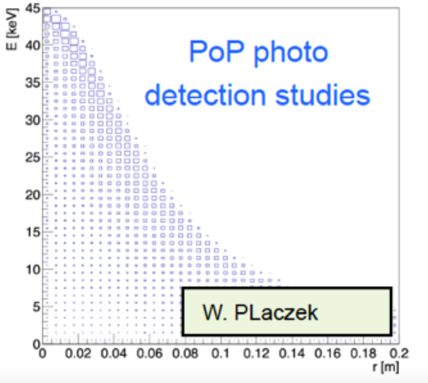
Pb^{79+}: γ at z = 6m, no emission delay

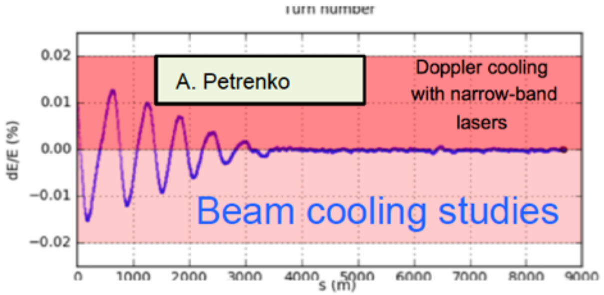


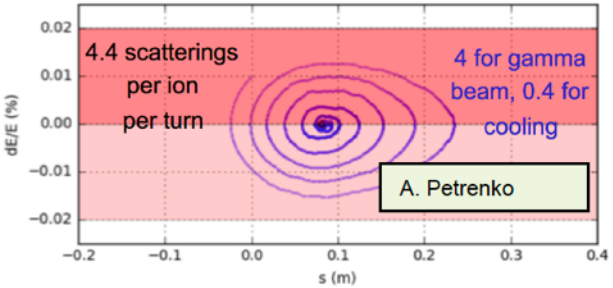
Gamma Factory: Pb^{79+}

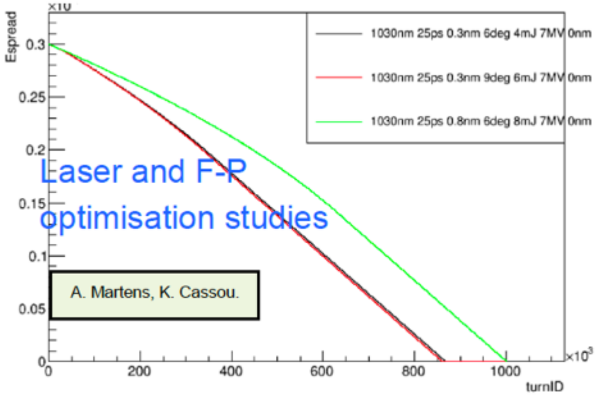


Pb^{79+}: γ at z = 6m, with emission delay

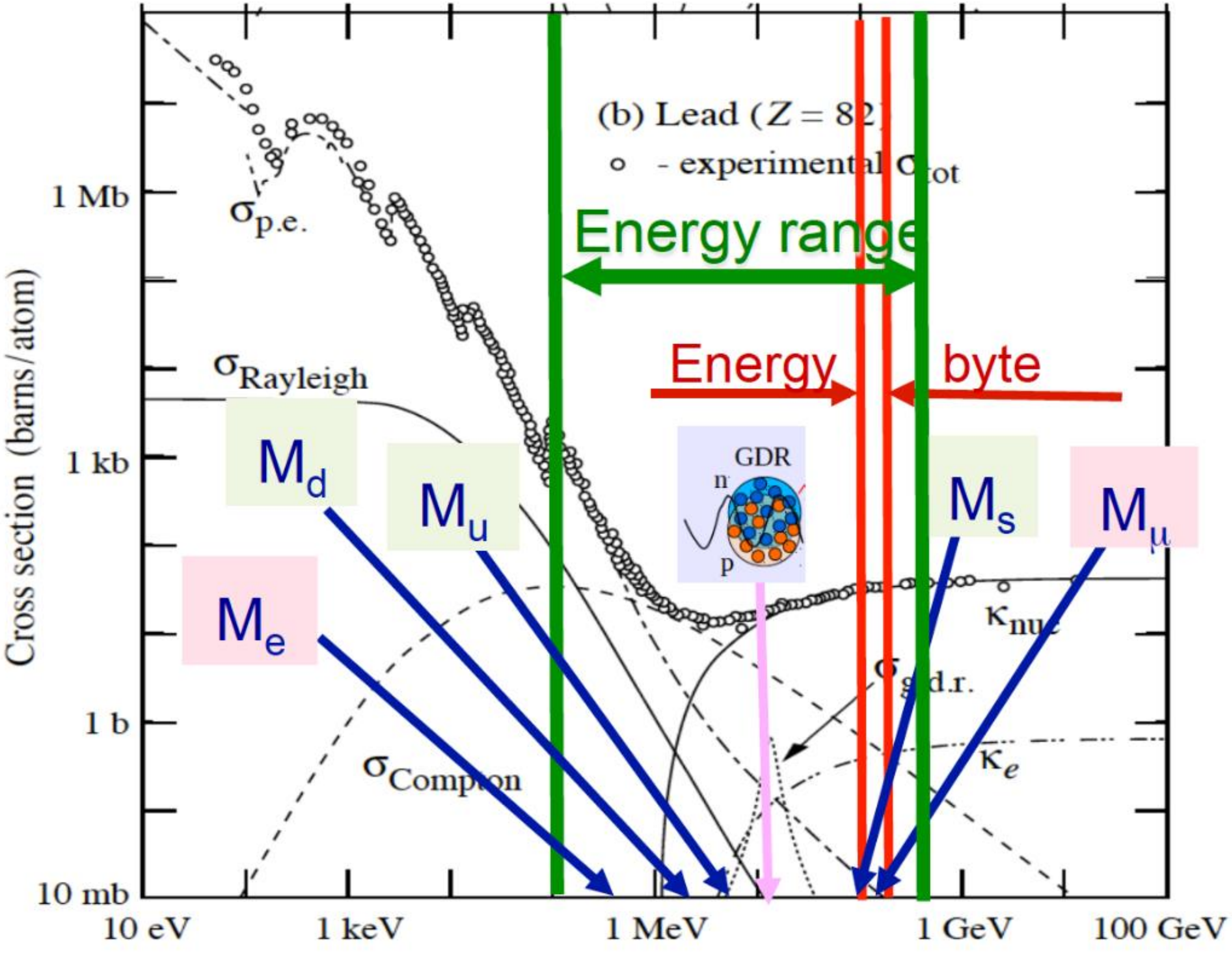








Potential


(b) Lead (Z = 82)
○ - experimental σtot
Energy range
Energy
byte
1 Mb
1 kb
1 b
10 mb
Cross section (barns/atom)
10 eV
1 keV
1 MeV
1 GeV
100 GeV
σp.e.
σRayleigh
σCompton
σg.d.r.
κnuc
κe
Md
Mu
Me
Ms
Mμ
GDR
n
p

The expected magnitude of the γ-source intensity leap

Electrons:

$\sigma_e = 8\pi/3 \times r_e^2$

r_e - classical electron radius

Partially Stripped Ions:

$\sigma_{res} = \lambda_{res}^2 / 2\pi$

λ_{res} - photon wavelength in the ion rest frame

Electrons:

$\sigma_e = 6.6 \times 10^{-25}\ \mathrm{cm}^2$

Partially Stripped Ions:

$\sigma_{res} = 5.9 \times 10^{-16}\ \mathrm{cm}^2$

Numerical example: $\lambda_{laser} = 1540$ nm

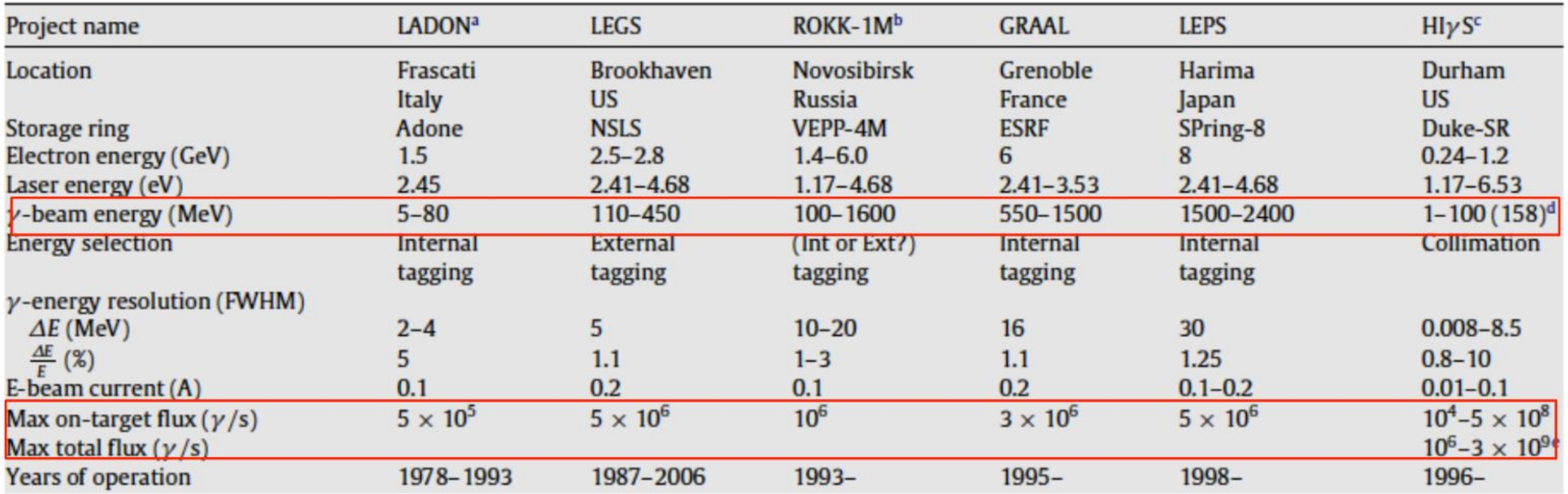
~ 9 orders of magnitude difference in the cross-section

~ 7 orders of magnitude increase of gamma fluxes

Caveat: should bear in mind that relativistic electrons are somewhat easier to produce than high energy PSIs!

Parameters of the γ-ray sources around the world

Doppler upshifting of intense laser sources; “monochromatic” source; intense electron beam needed



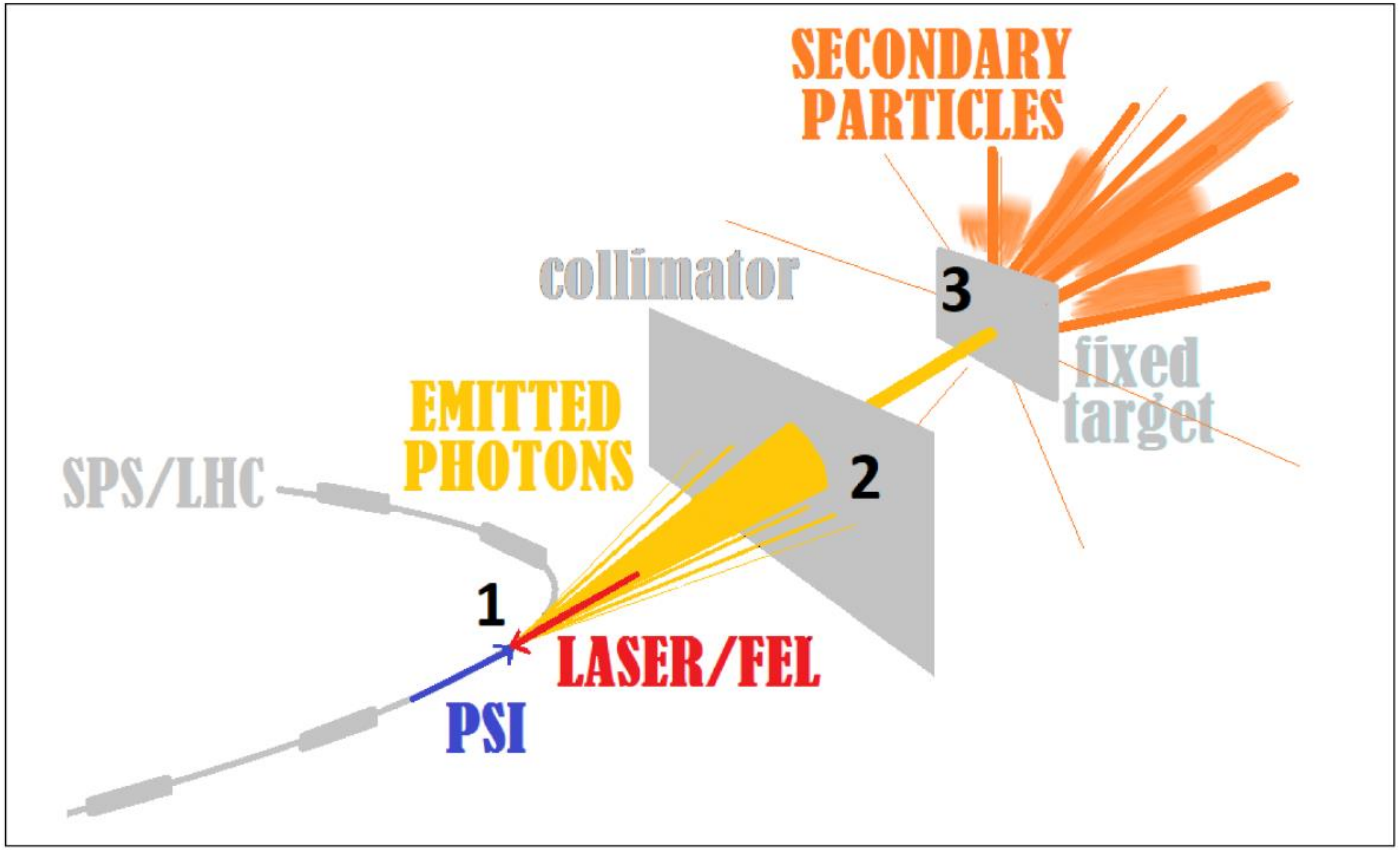
Project name	LADON[a]	LEGS	ROKK-1M[b]	GRAAL	LEPS	HIγS[c]
Location	Frascati Italy	Brookhaven US	Novosibirsk Russia	Grenoble France	Harima Japan	Durham US
Storage ring	Adone	NSLS	VEPP-4M	ESRF	SPring-8	Duke-SR
Electron energy (GeV)	1.5	2.5–2.8	1.4–6.0	6	8	0.24–1.2
Laser energy (eV)	2.45	2.41–4.68	1.17–4.68	2.41–3.53	2.41–4.68	1.17–6.53
γ-beam energy (MeV)	5–80	110–450	100–1600	550–1500	1500–2400	1–100 (158)[d]
Energy selection	Internal tagging	External tagging	(Int or Ext?) tagging	Internal tagging	Internal tagging	Collimation
γ-energy resolution (FWHM)						
ΔE (MeV)	2–4	5	10–20	16	30	0.008–8.5
$\frac{\Delta E}{E}$ (%)	5	1.1	1–3	1.1	1.25	0.8–10
E-beam current (A)	0.1	0.2	0.1	0.2	0.1–0.2	0.01–0.1
Max on-target flux (γ/s)	5×10^5	5×10^6	10^6	3×10^6	5×10^6	10^4–5×10^8
Max total flux (γ/s)						10^6–3×10^9
Years of operation	1978–1993	1987–2006	1993–	1995–	1998–	1996–

The Gamma Factory goal: achieve comparable fluxes in the MeV domain as those in the KeV domain – e.g. those of the DESY XFEL:

*(DESY FEL: photons/pulse -- 10^{11}-10^{13}, pulses/second –10-5000 →**(10^{12} – 10^{17} photons/s)***

An intensity jump of up to 3-8 orders of magnitude required !

Gamma Factory



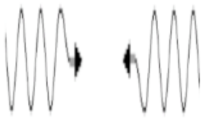
Gamma Factory research programme targets

Particle	*basic symmetries, **DM,** EW precision measurements with PSI, ion, μ and ν beams…*
Nuclear	*nuclear charge and spin structure**, neutron skin**, QCD confinement studies, photo-fission*
Accelerator	***beam cooling,** plasma wake field acc., high-int. polarized e & μ sources…*
Atomic	*physics of highly charged electronic and muonic atoms: strong EM fields, EW effects…*
Applied	*accelerator driven energy sources , cold? & warm fusion, medical isotope production…*

Physics

Collider schemes

collider schemes:

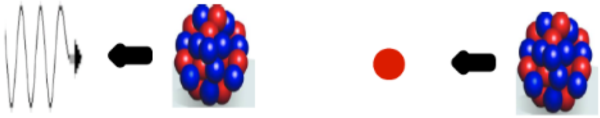


γ–γ collisions,

E_{CM} = 0.1 – 800 MeV

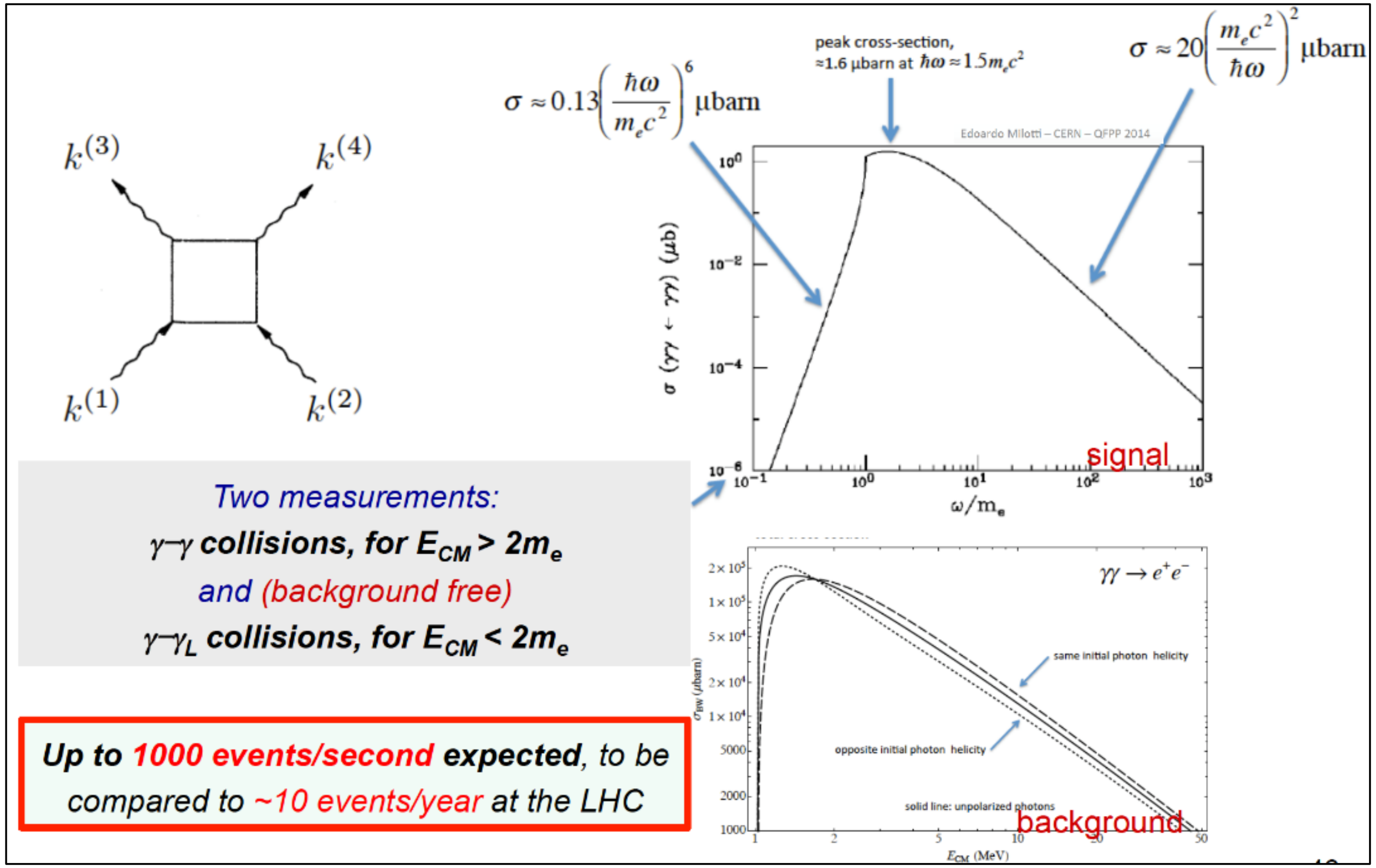
γ–γ_L collisions,

E_{CM} = 1 – 100 keV



γ–p(A), ep(A) collisions,

E_{CM} = 4 – 200 GeV



$\sigma \approx 0.13\left(\frac{\hbar\omega}{m_e c^2}\right)^6$ μbarn

peak cross-section,
≈1.6 μbarn at $\hbar\omega \approx 1.5 m_e c^2$

$\sigma \approx 20\left(\frac{m_e c^2}{\hbar\omega}\right)^2$ μbarn

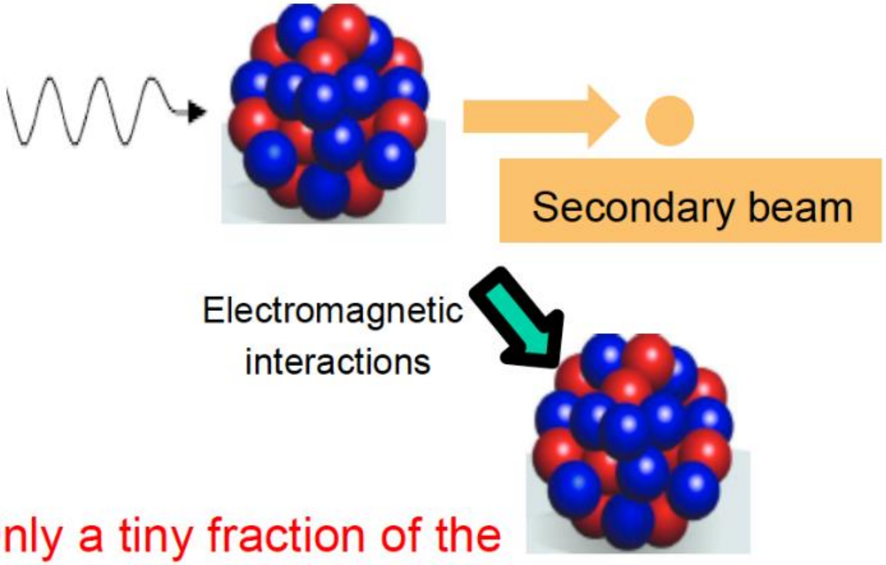
Two measurements:
γ–γ collisions, for $E_{CM} > 2m_e$
and (background free)
γ–γ_L collisions, for $E_{CM} < 2m_e$

***Up to 1000 events/second expected**, to be compared to ~10 events/year at the LHC*

Secondary beams

secondary beam sources:

- **polarised electrons,**
- **polarised positrons**
- **polarised muons**
- **neutrinos**
- **neutrons**
- **vector mesons**
- **radioactive nuclei**



Secondary beam

Electromagnetic interactions

Only a tiny fraction of the primary beam energy is wasted!

Initial estimates for secondary beam sources

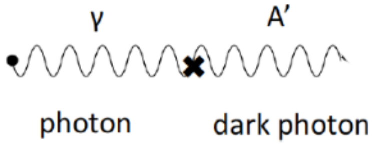
- **Polarised positrons**
  - up to 10^{17}/s
- **Polarised muons and neutrinos**
  - low emittance beams for muon collider, high purity neutrino beams
  - up to 10^{12}/s and up to 4 x 10^{19}/year
- **Neutrons**
  - GDR in heavy nuclei: $\gamma + A \rightarrow A - 1 + n$
  - up to 10^{15} /s, mono-energetic
- **Radioactive ions**
  - photo-fission $\gamma + A \rightarrow A_1 + A_2 + n$
  - up to 10^{14} /s

For the quoted flux the RF voltage would need to be increased and/or number of stored ions increased by a factor 2 to 3

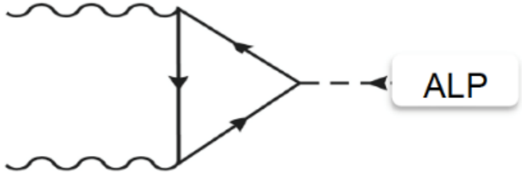
5. The unique Gamma Factory DM search opportunities in the region of interest

Principal portals accesible :

Dark Photon



Axion-like

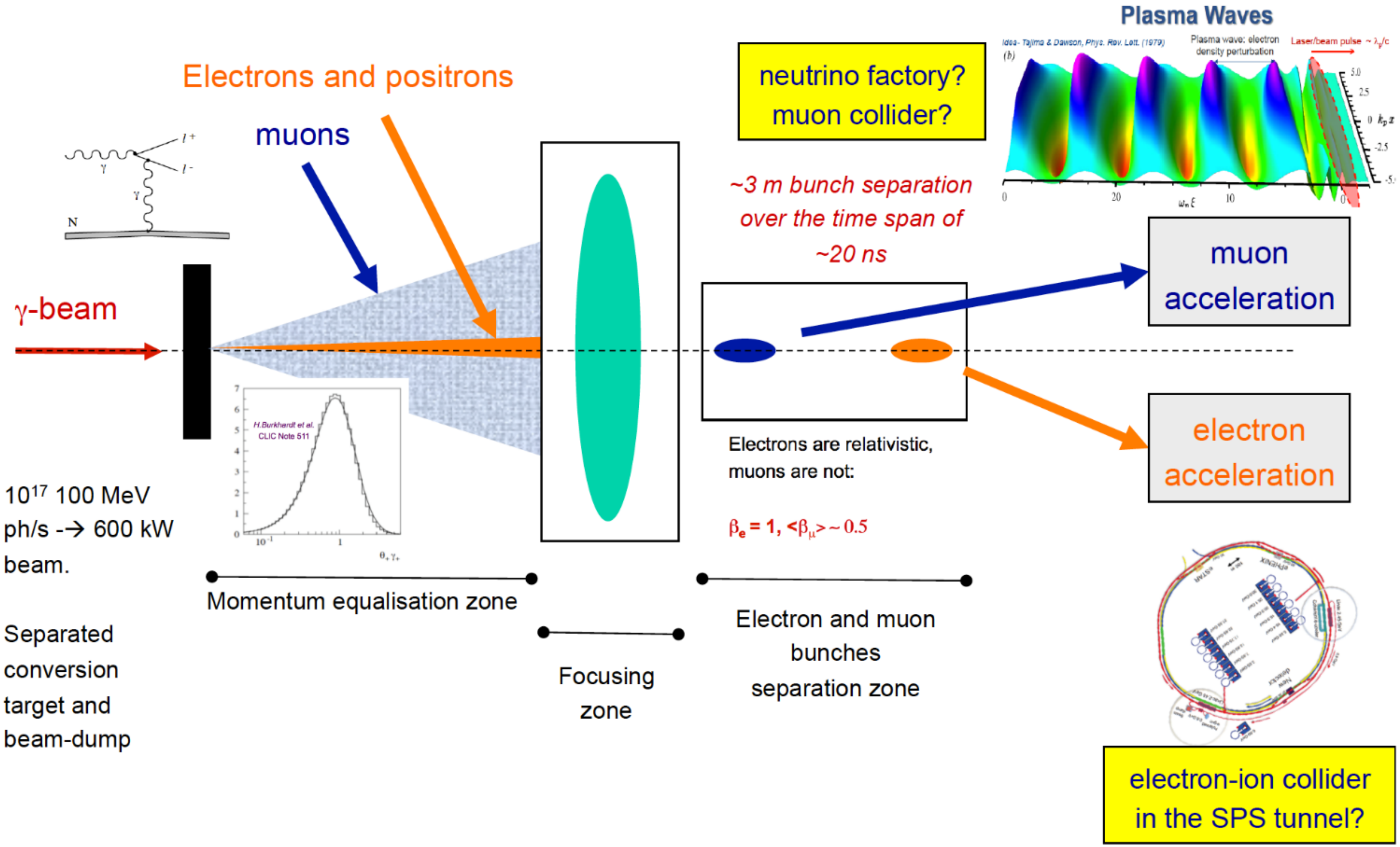


A very wide mass region(1 keV - 800 MeV) and a wide range of the production cross sections (down to the O(1) fb region) can be explored

Search sensitivity leap:

1. *Beam intensity for the beam dump type of experiment:* ***up to 10^{24} /year of dumped photons*** *(the SHIP yardstick: 10^{19} protons/year on target)*
2. *A comfortable timing structure of gamma beams (~10 MHz)*
3. *Direct Searches with a broad-band colliding gamma beams can be followed by dedicated resonance region investigations with a very narrow band beam*

6. and 7. New research opportunities with a high intensity polarised lepton-beam source ((6)electrons and (7) muons)



Electrons and positrons

muons

γ-beam

neutrino factory? muon collider?

~3 m bunch separation over the time span of ~20 ns

muon acceleration

electron acceleration

Electrons are relativistic, muons are not:

$\beta_e = 1$, $\langle\beta_\mu\rangle \sim 0.5$

10^{17} 100 MeV ph/s -→ 600 kW beam.

Separated conversion target and beam-dump

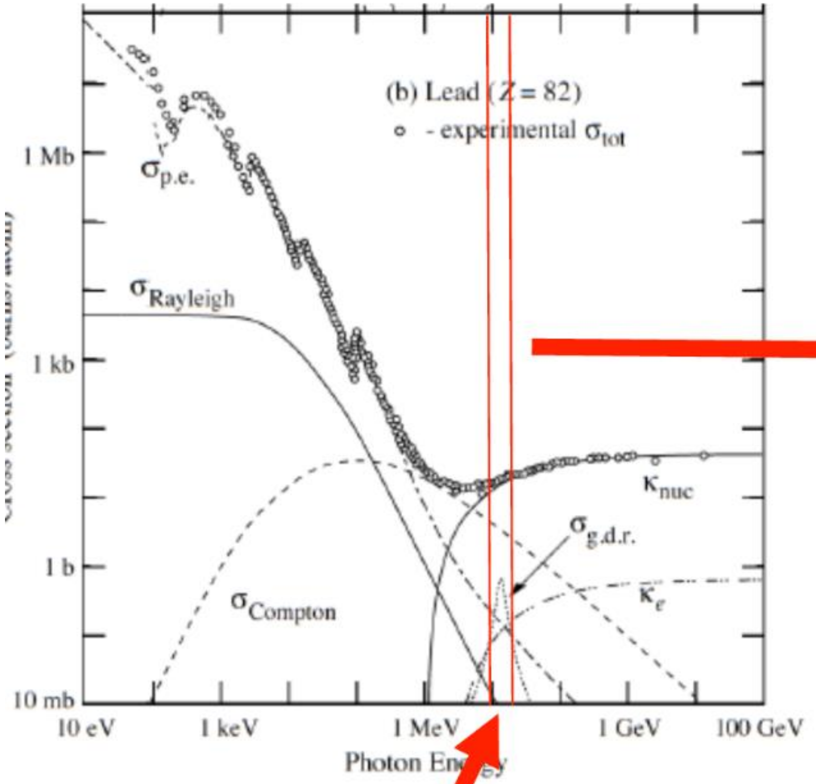
Momentum equalisation zone

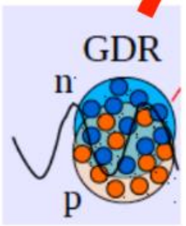
Focusing zone

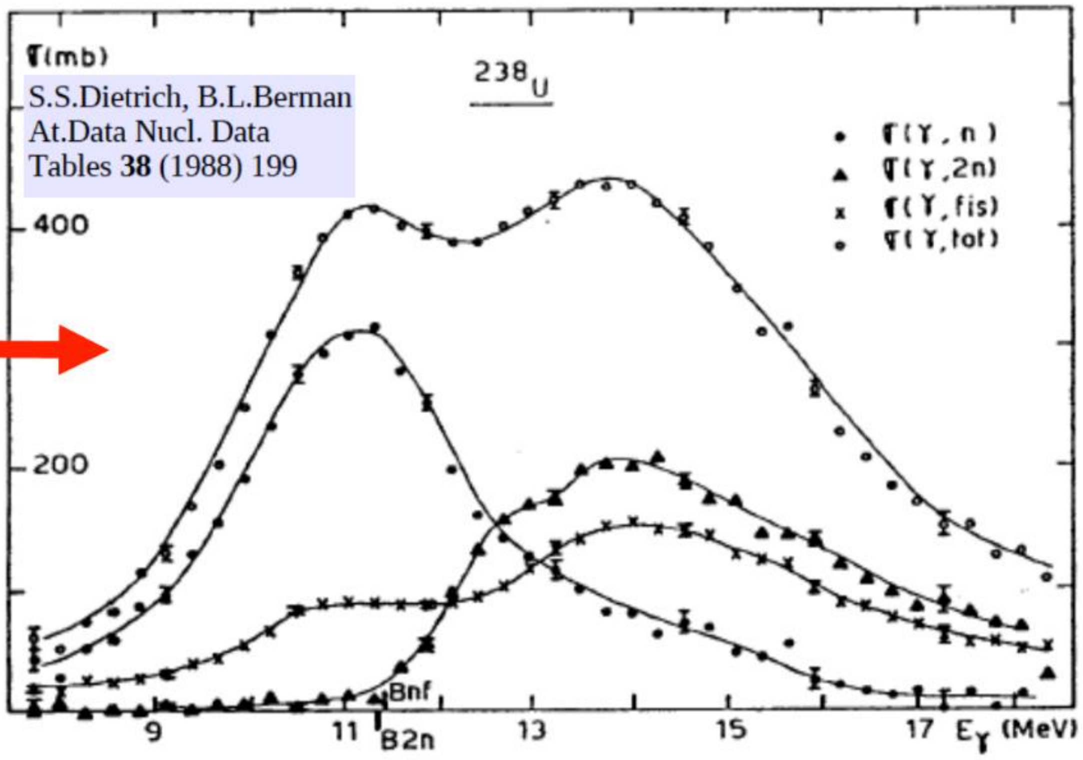
Electron and muon bunches separation zone

electron-ion collider in the SPS tunnel?

9.The nuclear physics research opportunities







S.S.Dietrich, B.L.Berman
At.Data Nucl. Data
Tables **38** (1988) 199

Figure 1. Partial and total photonuclear cross sections (γ,n), (γ,2n), (γ,f), and (γ,tot) for U^{238}.

The Gamma Factory production rate:

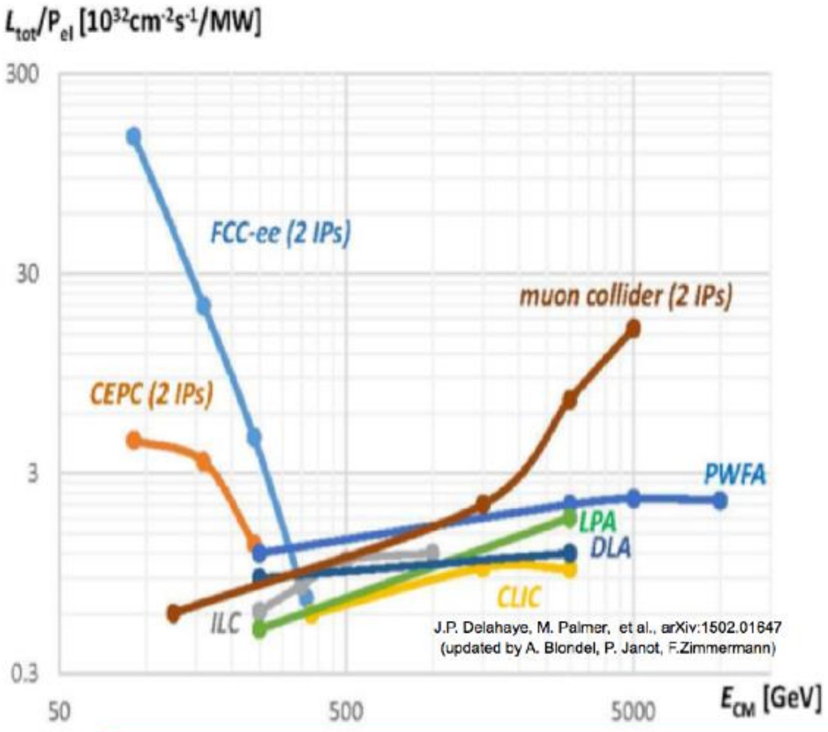
- *primary neutrons* ***up to 10^{15} 1/s***
- *fission products* ***up to 10^{14} 1/s***

GDR=Giant Dipole Resonance

Example: Variants of 100 TeV muon colliders based on the FCC and Gamma Factory concepts

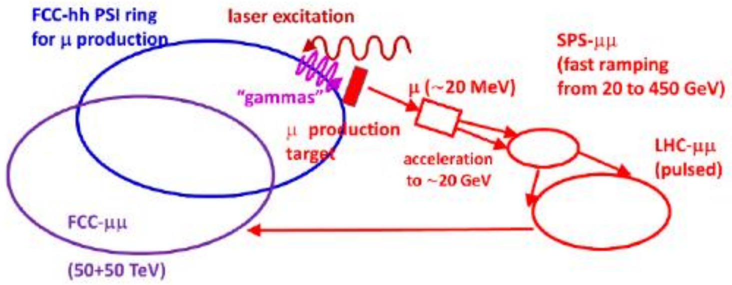
- Active interest in the possibility of a muon collider

- Big challenge is the production of intense, low emittance muons beams:
  - Proton driver
  - LEMMA
    (45 GeV positron ring → …)

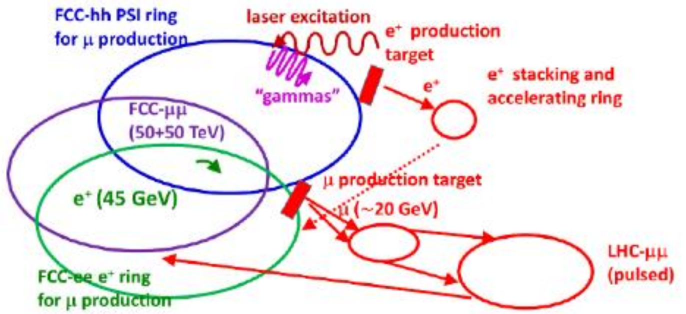


J.P. Delahaye, M. Palmer, et al., arXiv:1502.01647
(updated by A. Blondel, P. Janot, F.Zimmermann)

For the CM-energies above 2 TeV (10 fold increase w.r.t LEP) a muon collider appears to be the only way to achieve a requisite luminosity with reasonable wall power consumption



100 TeV μ collider FCC-μμ with FCC-hh PSI e^+ & FCC-ee $\mu^\pm$ production



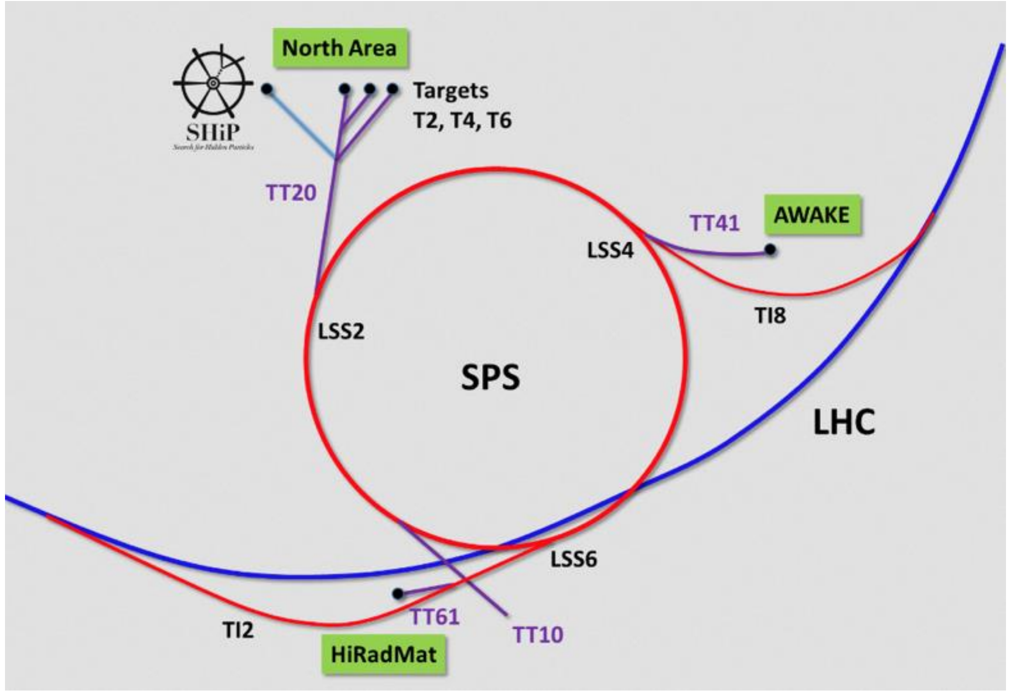
LHC/FCC-BASED MUON COLLIDERS*

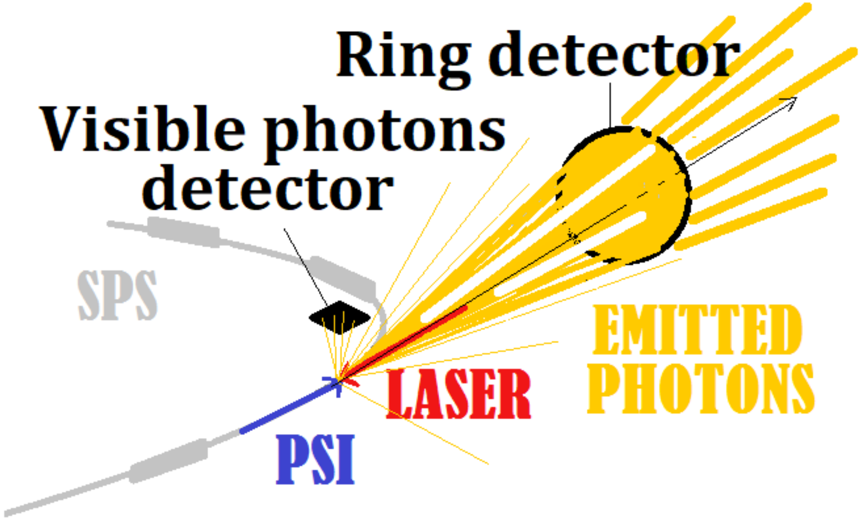
F. Zimmermann†, CERN, Geneva, Switzerland

Phasing in

- GF potential looks impressive, however investment for full-scale implementation is in competition with existing, and proposed, projects
- Staged approach to demonstrate full-scale feasibility…

Scenario	Ion beam	Eγ (max)	
S1	**Li-like Pb in LHC (2s→3p)$_{1/2}$**	**87 MeV**	**Minimal interference with ion programme**
S2	**Li-like Pb in LHC (2s→2p)$_{3/2}$**	**15 MeV**	**Minimal interference with ion programme**
S3	H-like Xe (1→2p)$_{1/2}$	182 MeV	Going to highest gamma energies GF high energy frontier – DM searches
S4	He-like Ca (1s→2p)$_{3/2}$	26 MeV	GF high intensity frontier – Nuclear Physics & Applied Physics
S5a	**Li-like Ca (2s→3p)$_{1/2}$ (SPS)**		**SPS cooling, followed by Ca-Ca collisions in the LHC** **$L_{Ca-Ca} = 6.2 \times 10^{31}$ cm^{-2}s^{-1} – present program**
S5b	**H-like Pb (say)**		**LHC electron-proton collisions – present program**





Next Step: Proof of Principle - SPS

Main objectives

- Verify of simulations on rate of atomic excitation
- Demonstrate matching of characteristics of ion bunches to those of the laser bunches, match laser spectrum to width of the atomic excitation and achieve resonance for adequate fraction of ion population
- Measure emitted X-rays, characterisation of flux and spectrum, and demonstration of photon extraction from the collision zone
- Demonstrate integration and operation of laser and Fabry-Perot cavity in a hadron storage ring

Ambition/complexity/cost cut-off

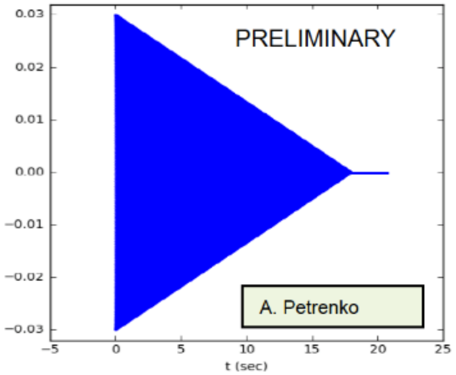
- Demonstrate laser cooling of relativistic beams and investigation of the different approaches
- Demonstrate feasibility of relativistic Atomic Physics measurements.

Choice of ion for PoP experiment

➤ *Lithium-like Lead:* **Pb+79**

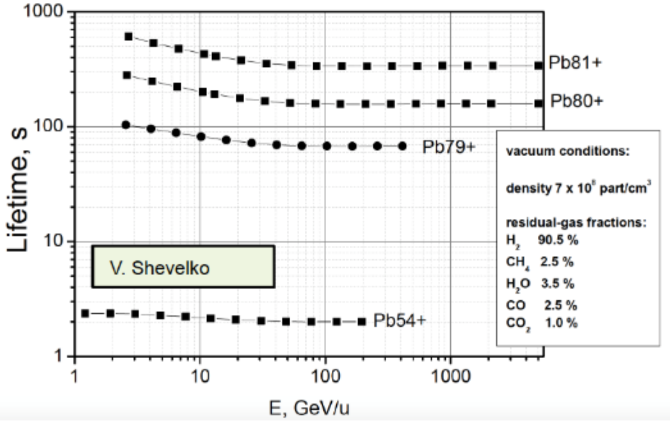
- ATOMIC GROUND STATE: $1s^2\,2s^1\ {}^2S_{1/2}$
- CHOICE OF EXCITED STATE: $1s^2\,2p^1\ {}^2P_{1/2}$
- TRANSITION ENERGY: **E = 230.76 eV**
- LIFETIME (excited state): τ **= 76 ps**
- ION LORENTZ FACTOR: γ_L **= 96**
- PULSED LASER: λ_{laser} **= 1030 nm**

Cooling time in the SPS
(~1 photon absorption/revolution/ion)



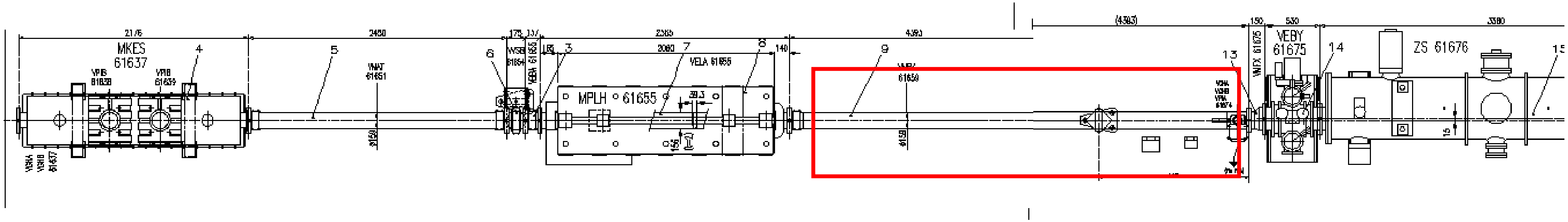
$\tau_{cooling} < \tau_{beam}$

Pb+79 beam life-time in the SPS



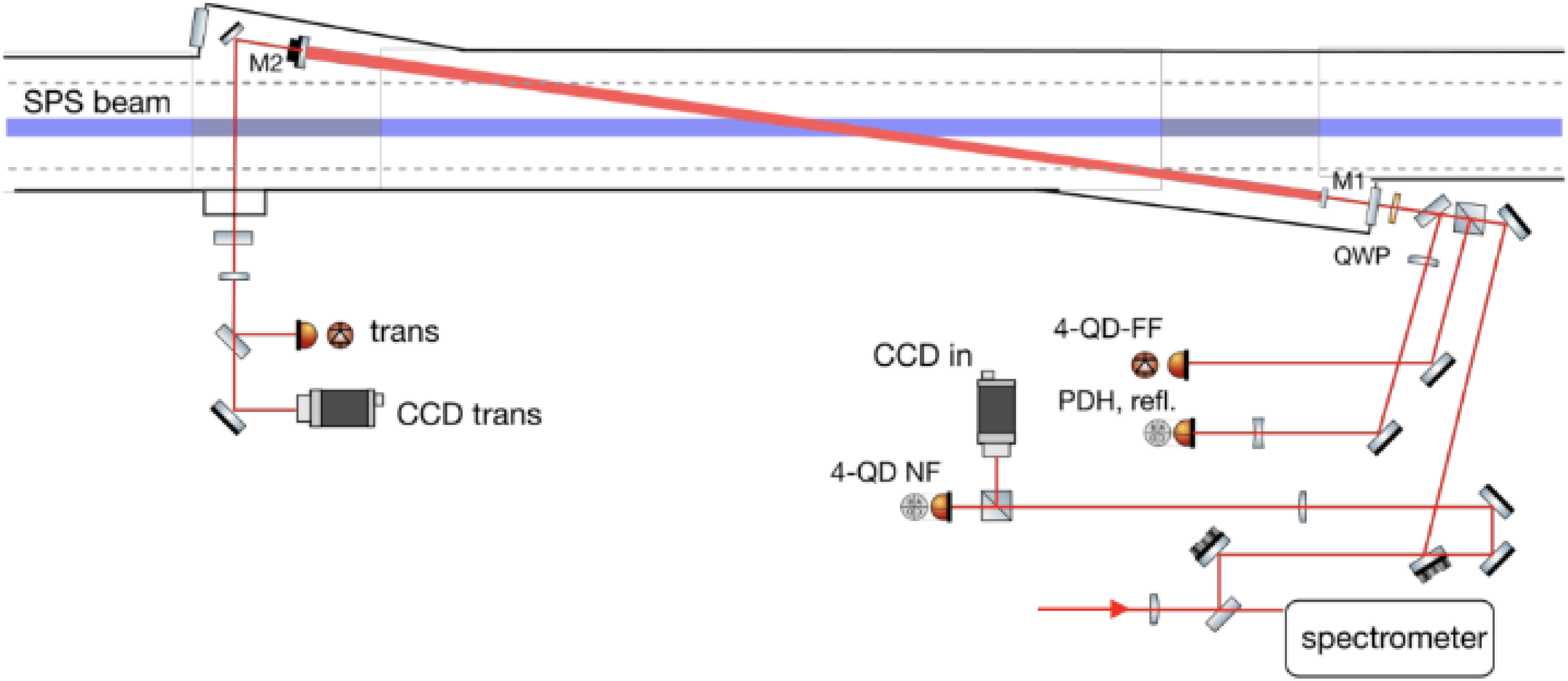
Parameter	Value
crossing angle	2.6°
Ion magnetic rigidity	787 T m
Ion γ factor	96.3
Ion beam horizontal RMS size at IP	1.3 mm
Ion beam vertical RMS size at IP	0.8 mm
Ion revolution frequency	43.4 kHz
Laser photon energy	1.2 eV
Laser frequency	40 MHz
Laser pulse energy	5 mJ
Ion $2s_{1/2} \rightarrow 2p_{1/2}$ transition energy	230.8 eV
Maximum energy of back scattered photon	44.5 keV

Laser-PSI interaction region: tentatively SPS LSS6



- About 4.4 m flange-flange between MPLH and ZS (VV)
- 2.6 degree cavity, **4 mJ** laser pulse energy at IR

FP cavity on SPS beam (vertical crossing?)

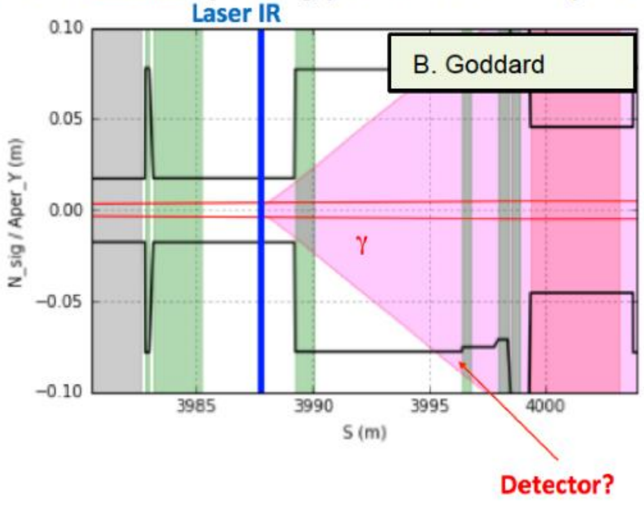


Diagnostics

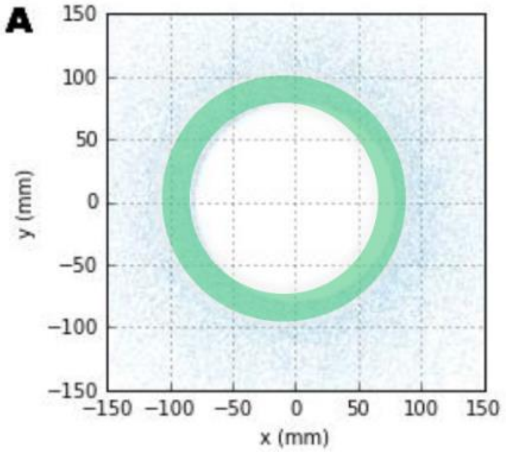
- Measure beam overlap
- Measure X-ray photon beam properties
- Measure beam cooling

Large flux of x-ray photons in > 10 keV range after 10 m

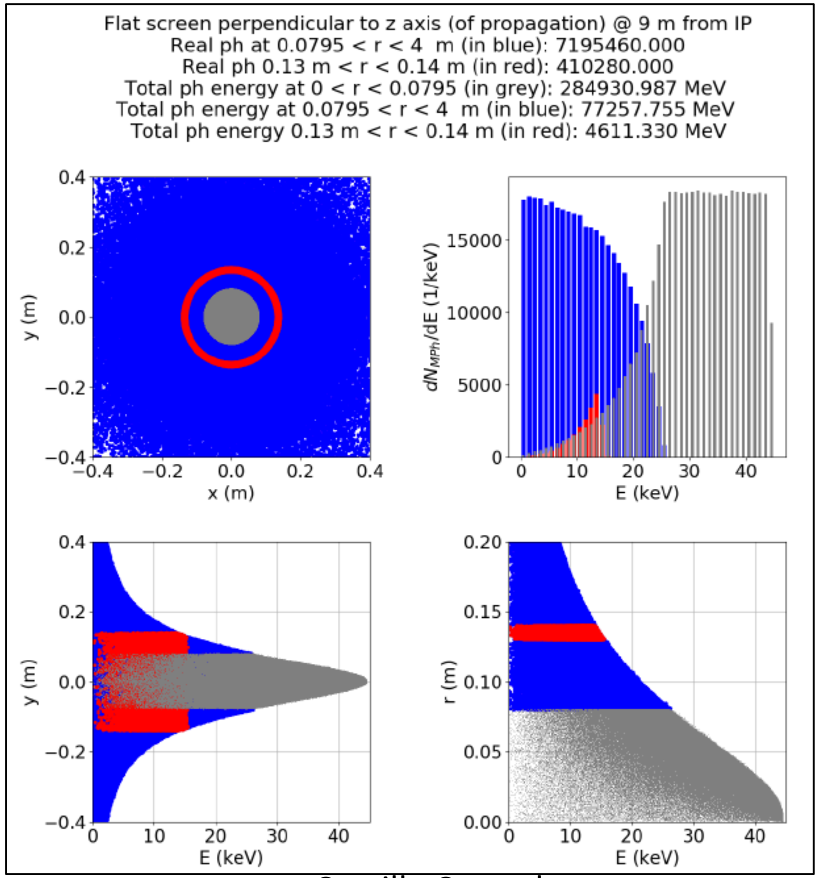
- X-ray cone with 11 mrad opening plotted in SPS aperture



Assuming a ring shaped detector (transverse size 1cm) located around the beam (d=80 mm)



Photon Flux



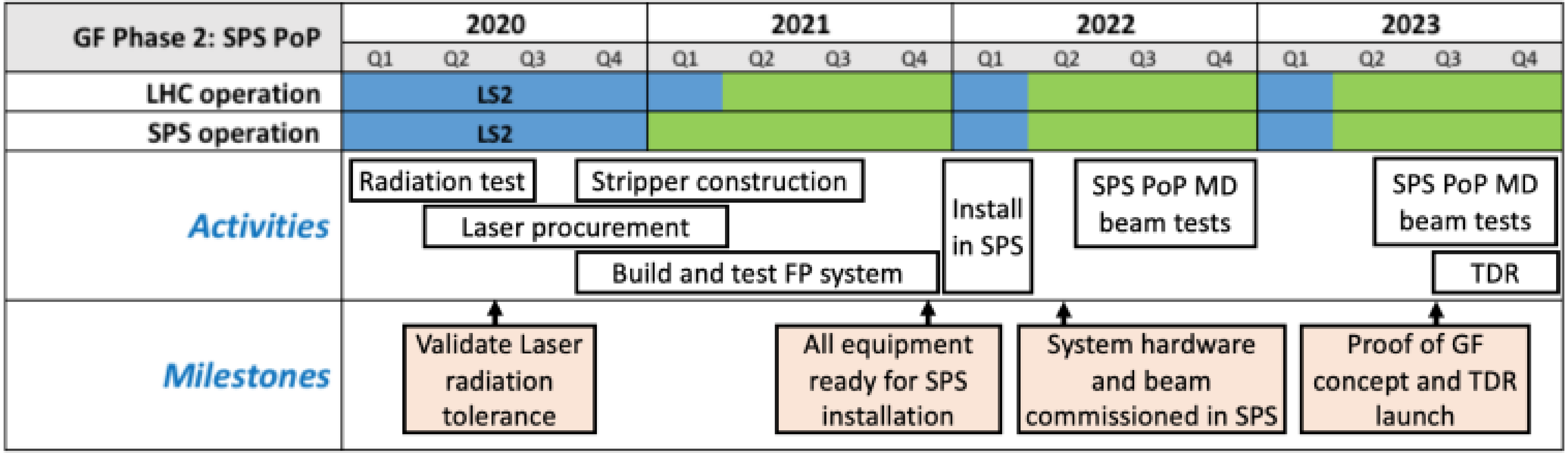
Camilla Curatolo

Status / open questions!

- Ion species and transition: defined (pb79+, 2s→2p)
- Ion beam parameters: defined
- IR location: identified (IR6). Confirm?
- SPS optical parameters: Defined (for LSS6)
- IR layout & FP design: proposed 2.6 deg crossing.
- Laser characteristics: in progress.
- Timing & synchronisation aspects: in progress
- Radiation aspects: 2018 dosimetry measurements: in progress
- Simulation benchmarking: in progress
- Parameter list (including uncertainties): in progress
- Emitted photon distribution f(t): in progress
- PSI beam 6D evolution f(t): in progress
- Detector requirements: in progress
- Experimental procedures: in progress
- Atomic physics prospects: to define

PoP Deadlines: phase 2

- Systems ready for installation: End December 2021 (30 months)
- Beam tests: 2022 and 2023

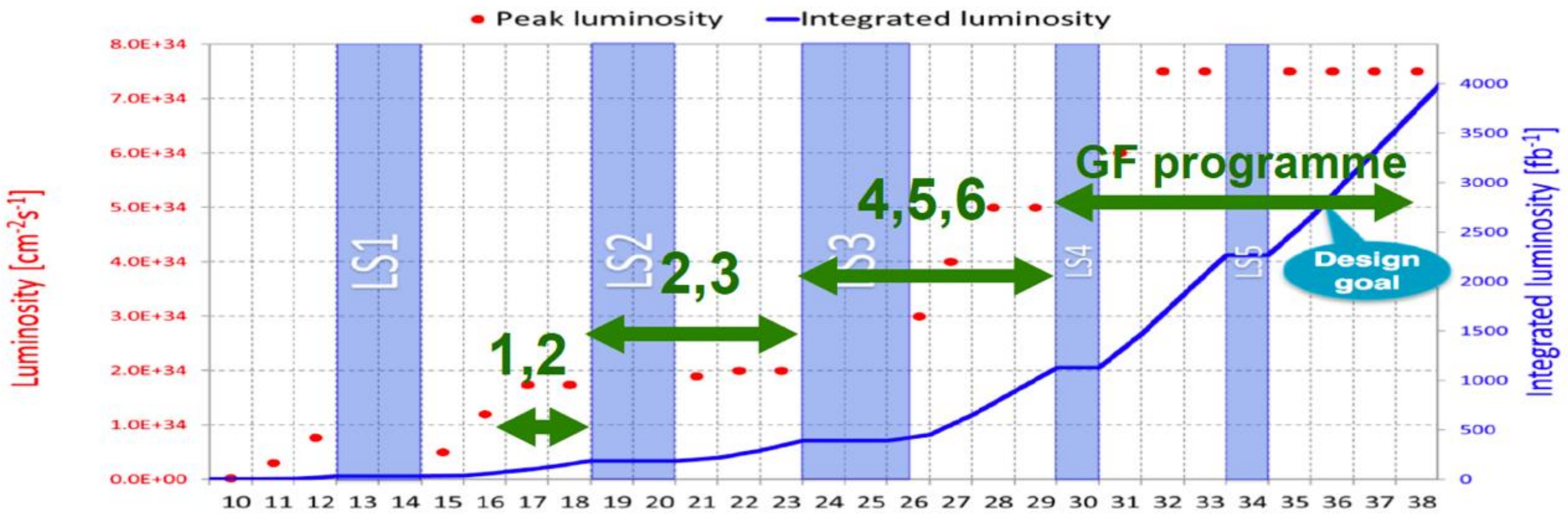


GF Phase 2: SPS PoP	2020				2021				2022				2023			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
LHC operation	🟦 LS2	🟦	🟦	🟦	🟦	🟩	🟩	🟩	🟦	🟩	🟩	🟩	🟦	🟩	🟩	🟩
SPS operation	🟦 LS2	🟦	🟦	🟦	🟩	🟩	🟩	🟩	🟦	🟩	🟩	🟩	🟦	🟩	🟩	🟩
Activities	Radiation test															
		Laser procurement														
				Stripper construction												
				Build and test FP system												
									Install in SPS	SPS PoP MD beam tests				SPS PoP MD beam tests		
															TDR	
Milestones			Validate Laser radiation tolerance					All equipment ready for SPS installation		System hardware and beam commissioned in SPS					Proof of GF concept and TDR launch	

Fig. 2: The timeline of the Gamma Factory SPS PoP experiment, Phase 2 activities – years 2020–2023.

Gamma Factory Project Milestones

1. Production, acceleration and storage of "atomic beams" at CERN
2. Development "ex nihilo" the requisite Gamma Factory software tools.
3. Proof-of-Principle experiment in the SPS tunnel.
4. Realistic assessment of the Gamma Factory performance figures.
5. Physics highlights of the Gamma Factory based research program.
6. Gamma Factory TDR



Conclusions

- Over the last 1.5 years the Gamma Factory initial ideas developed into a well defined project involving a group of around 50 physicists.
- Progress has been impressive. The next steps are clear.
- The target of the GF initiative is to develop the potential of a variety of novel research tools which could potentially open new opportunities in a broad domain of basic and applied science.

- It's an interesting phase for accelerator based HEP research – with no strong theoretical guidance for the mass scale of new physics, nor a mature, affordable technology for a leap into high energy "terra incognita" – high risk, high gain initiatives become important.

This what we should be doing!