Impact of vacuum quality in light sources: beam lifetime and ion instabilities

U. Iriso

ALBA - CELLS

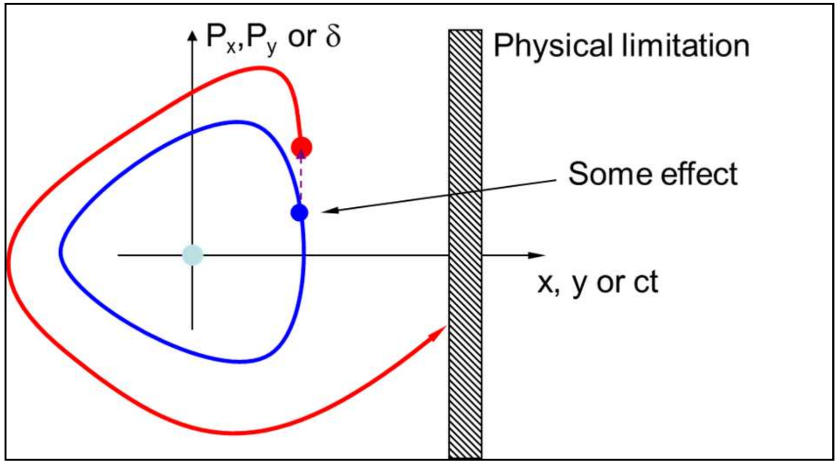
OUTLINE

1. Beam Lifetime
   a) Analytical description
   b) Observations in Light Sources

2. Ion Instabilities
   a) Analytical description
   b) Observations in Light Sources

3. Conclusions

Lifetime: Particle Loss in LS

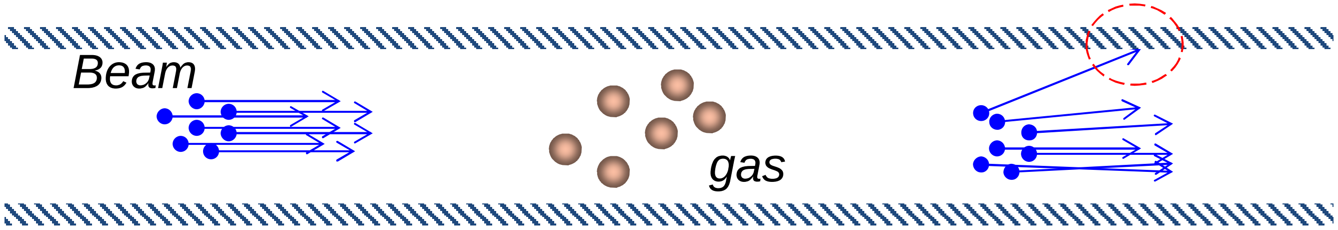


Main Lifetime contributors:

1. **Gas Lifetime**:
   Interactions with residual gas nucleus or electrons (elastic or inelastic)
2. **Touschek effect**:
   Interactions among beam particles with energy transfer.
3. **Quantum Lifetime**:
   Emission of radiation quanta when particles are close to the aperture limitations. Usually negligible, since it is ~1e5h or more.

Elastic Gas Scattering

Deflections caused by the **electrical force** of the residual gas atoms



Simplified Eqs*:

$$\frac{1}{\tau_{\text{nuclei-elastic}}} \approx \frac{2\pi r_e^2 c Z^2}{k_B T \gamma^2} \frac{\langle P_i \cdot \beta_{y_i} \rangle}{A^2} .$$

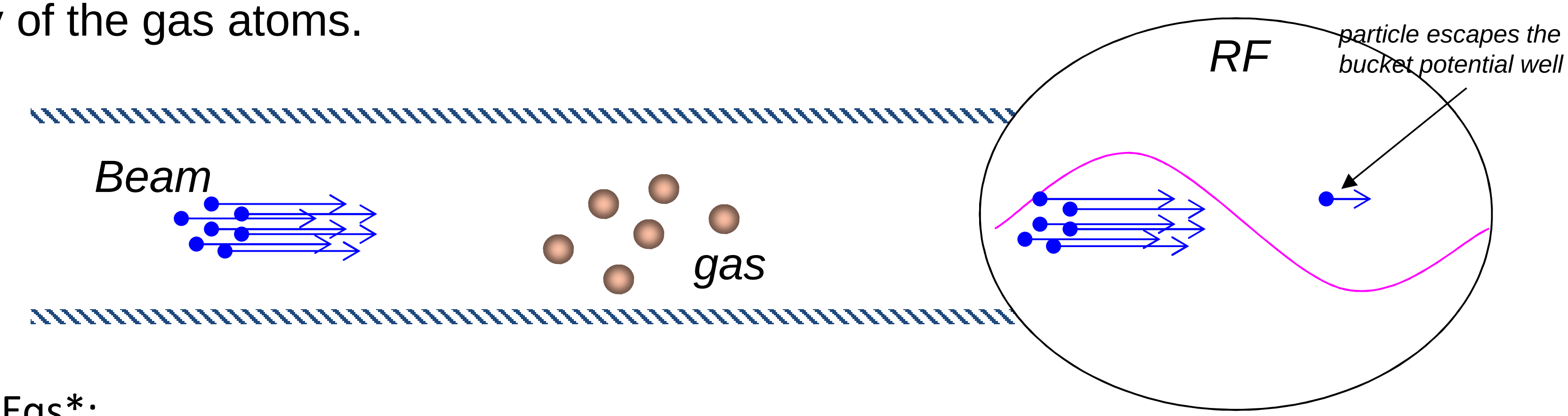
$$\frac{1}{\tau_{\text{electron-elast}}} \approx \frac{2\pi r_e^2 c P Z}{k_B T \gamma} \frac{1}{\delta_{\text{acc}}}$$

Note for LS, e-elast ~ [2-3] orders of magnitude larger

• Number of residual particles (pressure):	P↑→τ↓
• Particle Charge:	Z↑→τ↓
• Beta function.	β↑ →τ↓
• Vacuum chamber:	A↑→τ↑
• Beam energy:	γ↑ →τ↑

Inelastic Gas Scattering

Energy loss caused by **radiation emission (mostly)** at the vicinity of the gas atoms.



Simplified Eqs*:

$$\frac{1}{\tau_{\mathrm{nuclei-inelast}}} \approx \frac{4 r_e^2 c P Z^2}{137 k_B T} \frac{4}{3} \ln\left(\frac{183}{Z^{1/3}}\right)\left[\ln\left(\frac{1}{\delta_{\mathrm{acc}}}\right) - \frac{5}{8}\right]$$

$$\frac{1}{\tau_{\mathrm{electron-inelast}}} \approx \frac{4 r_e^2 c P Z}{137 k_B T} \frac{4}{3} \ln\left(\frac{2.5\gamma}{\delta_{\mathrm{acc}}} - 1.4\right)\left[\ln\left(\frac{1}{\delta_{\mathrm{acc}}}\right) - \frac{5}{8}\right]$$

Both shall be accounted for LS

1. Number of residual particles (pressure): $P \uparrow \rightarrow \tau \downarrow$
2. Charge of every particle: $Z \uparrow \rightarrow \tau \downarrow$
3. RF acceptance. $\delta_{acc} \uparrow \rightarrow \tau \uparrow$

Touscheck Lifetime (I)

- **Limiting effect in LS** (although not in the scope of this workshop)
- Due to energy exchange between particles within the bunch, which can bring the particles out of the energy acceptance
- It is not exponential, but assymptotic:

$$\frac{dN(t)}{N(t)dt} = -aN(t) \longrightarrow N(t) = \frac{N_0}{1+t/\tau}$$

- τ complex expression*, but its main dependencies:

$$\tau_t \propto \frac{\sqrt{\varepsilon_y}\sigma_z}{I_b}\delta_{acc}^3$$

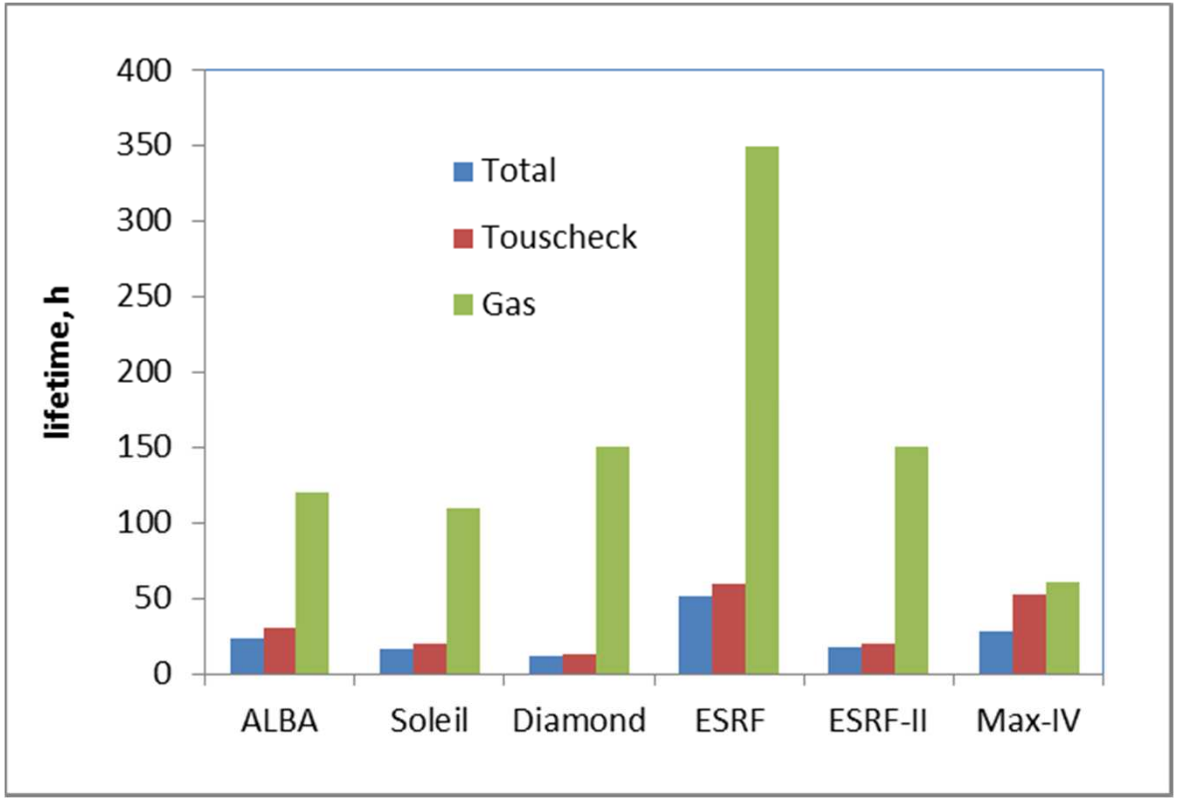
➔ **Product τ* I_b = ct** , widely used in LS (instead of τ)

1. V_{RF} ↑→ RF acceptance — δ_{acc}↑→τ↑
2. Beam density (coupling, bunch length). — ρ↑→τ↓
3. Beam bunch intensity: — I_b ↑→τ↓

*See Piwinsky Equation, Chao's book

Lifetime in LS

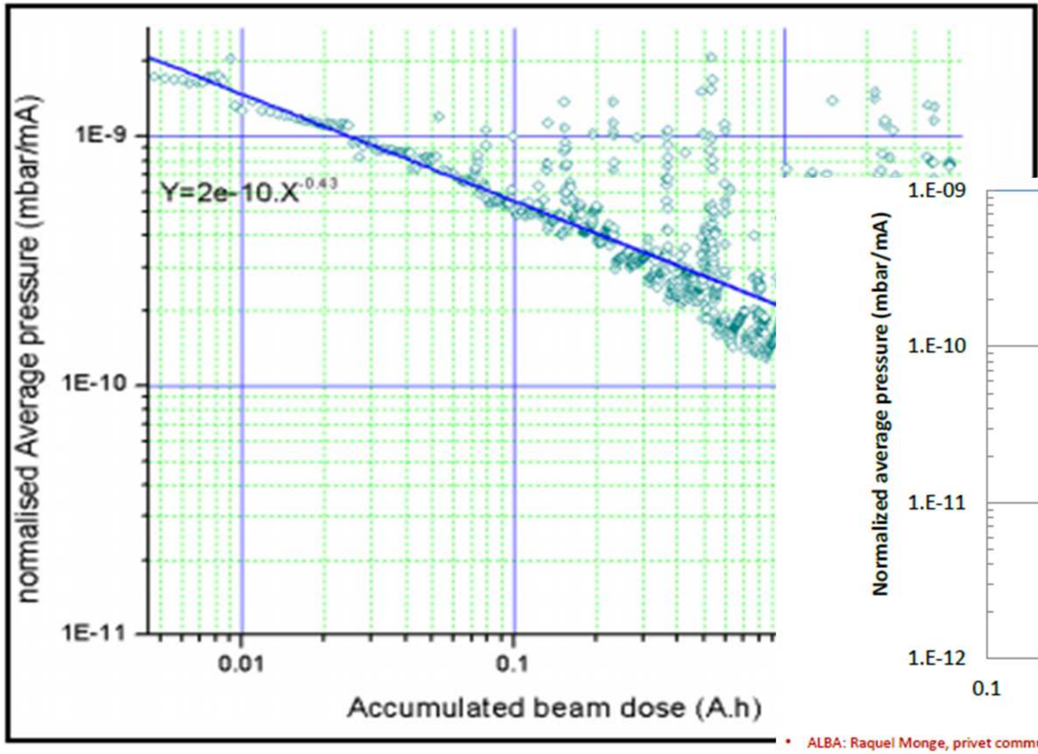
- Lifetime in LS is dominated by Touscheck effect, except in MAX-IV prediction@500mA
- Gas lifetime (including elastic & inelastic) only important at early commissioning phases or during installation of new IDs



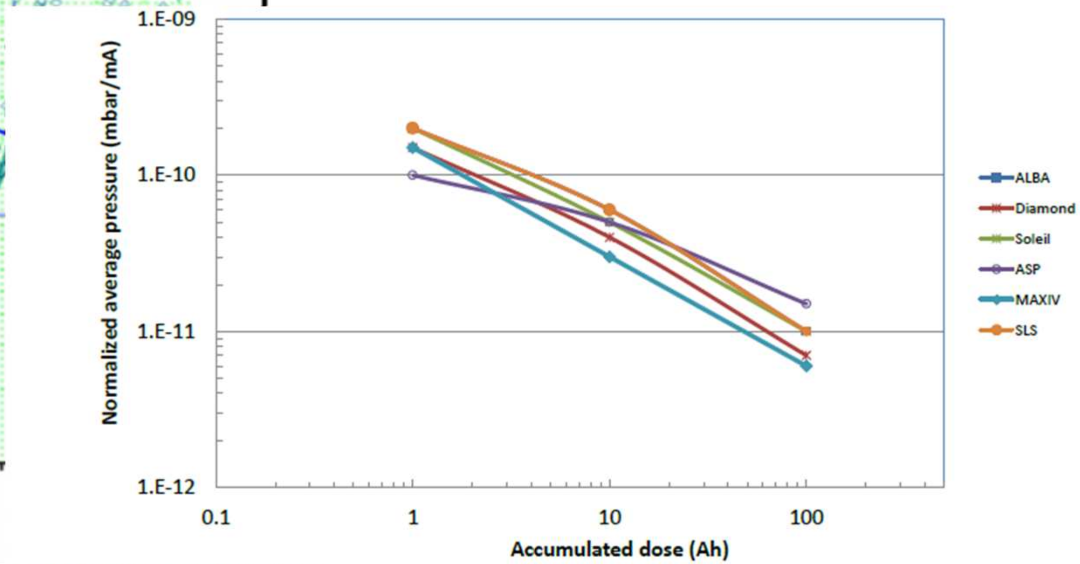
Soleil: X.N. Gavalda, Phd Thesis
Diamond: I. Martin, priv. communications
ESRF: N. Carmignani, priv. communications
MAX-IV: S.C. Leeman, PRST-AB 12, 120701 (2009) – **500mA**

Gas Lifetime in LS: commissioning

- Rule of thumb: Gas lifetime ~100h, when P-avg<1e-9, which is usually achieved after ~100 A*h
- At ALBA, this was achieved after ~6 months of operation



D. Einfeld, IPAC11

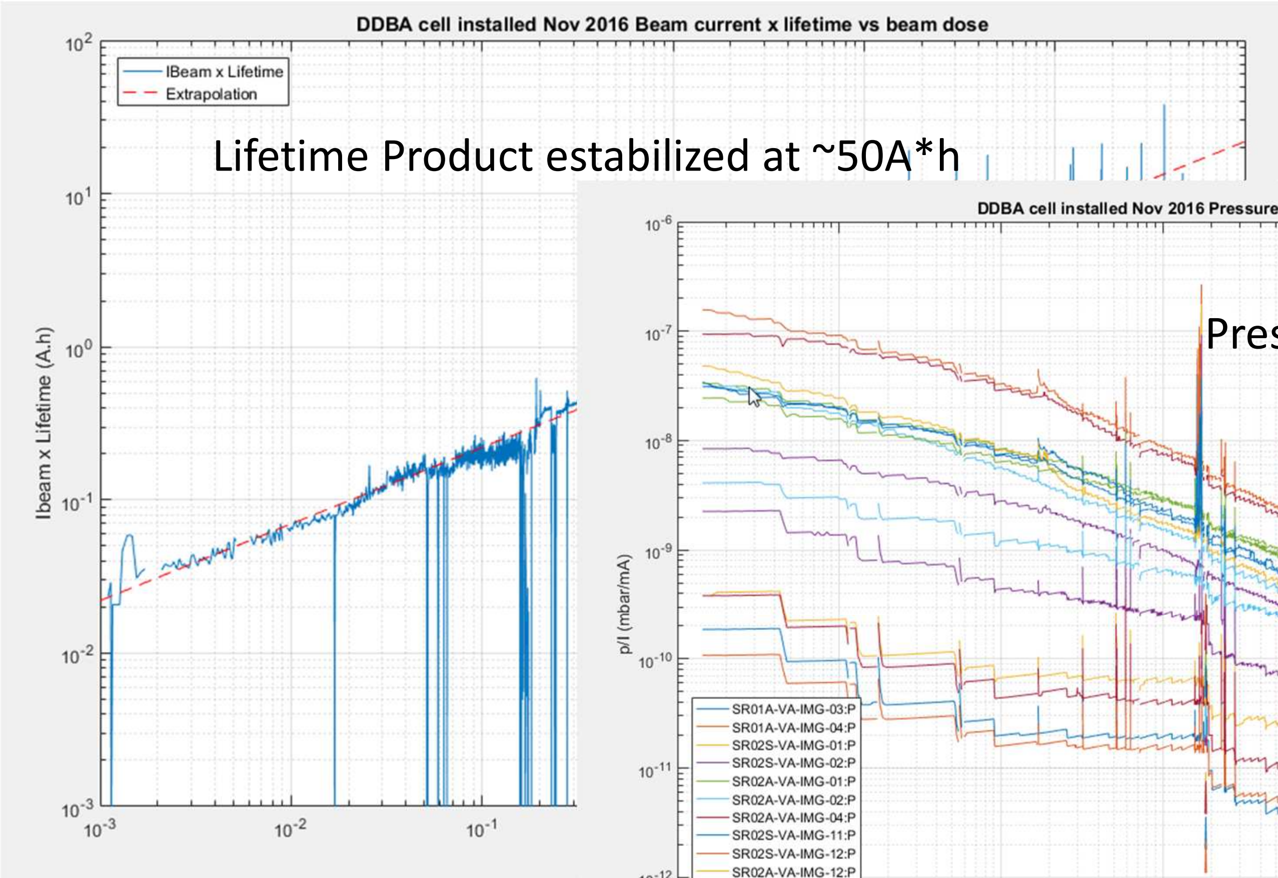


- ALBA: Raquel Monge, privet communication.
- Diamond: M P Cox et al, Commissioning of the diamond light source storage ring vacuum system, Journal of Physics: Conference Series 100 (2008) 092011
- Soleil: J.C. Besson, et al COMMISSIONING & OPERATION OF SOLEIL, WAO 2007. PSI - Scientific and Technical Report 2003 / Volume VI
- SLS: L. Schulz et al, STATUS REPORT OF THE SLS STORAGE RING VACUUM SYSTEM: EXPERIENCE AFTER TWO YEARS OF OPERATION
- ASP: E. Al-Dmour, VACUUM PERFORMANCE IN THE MOST RECENT THIRD GENERATION SYNCHROTRON LIGHT SOURCES, EPAC08.

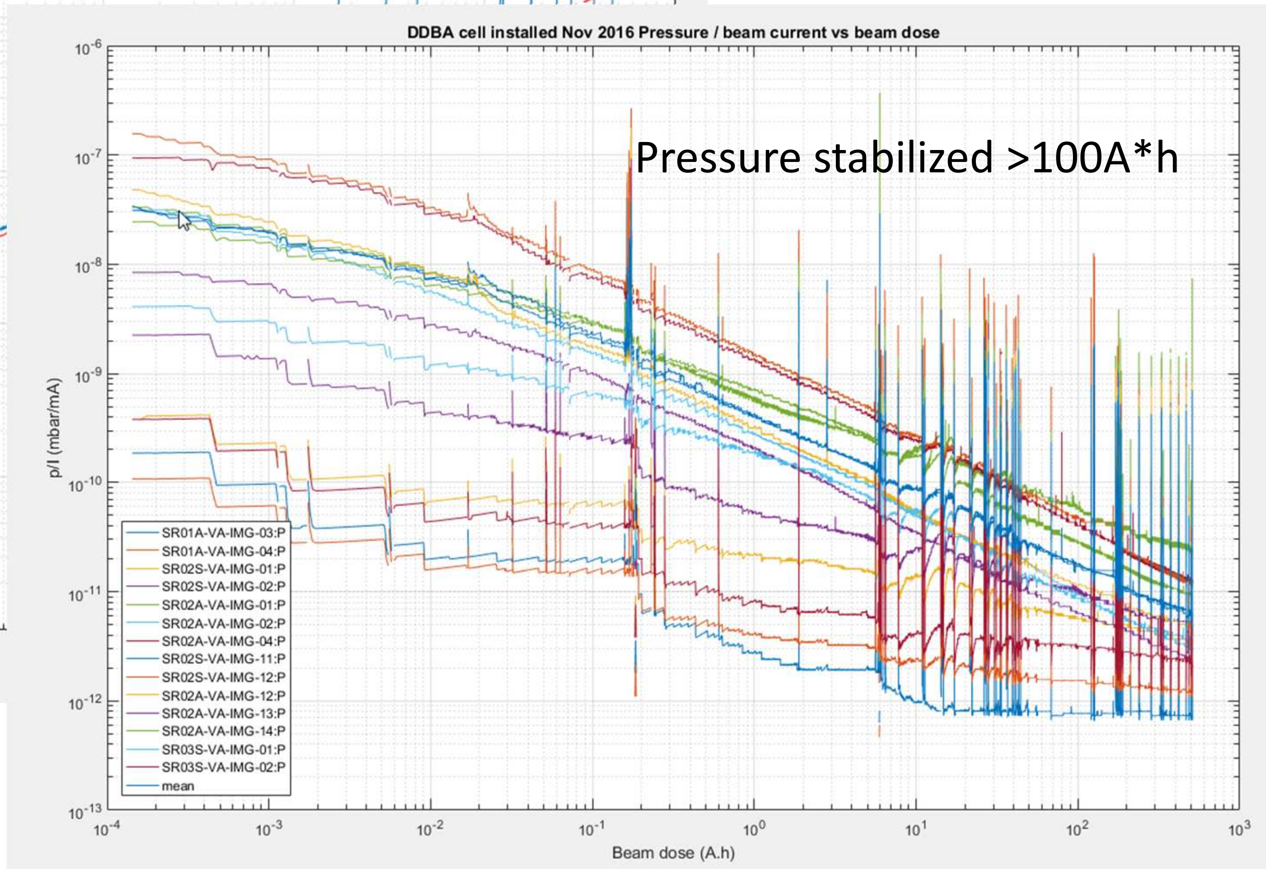
E. Al-Dmour, XXIV SLS Workshop, 2016

Installation of new components

Example: Complete Cell exchange in Diamond

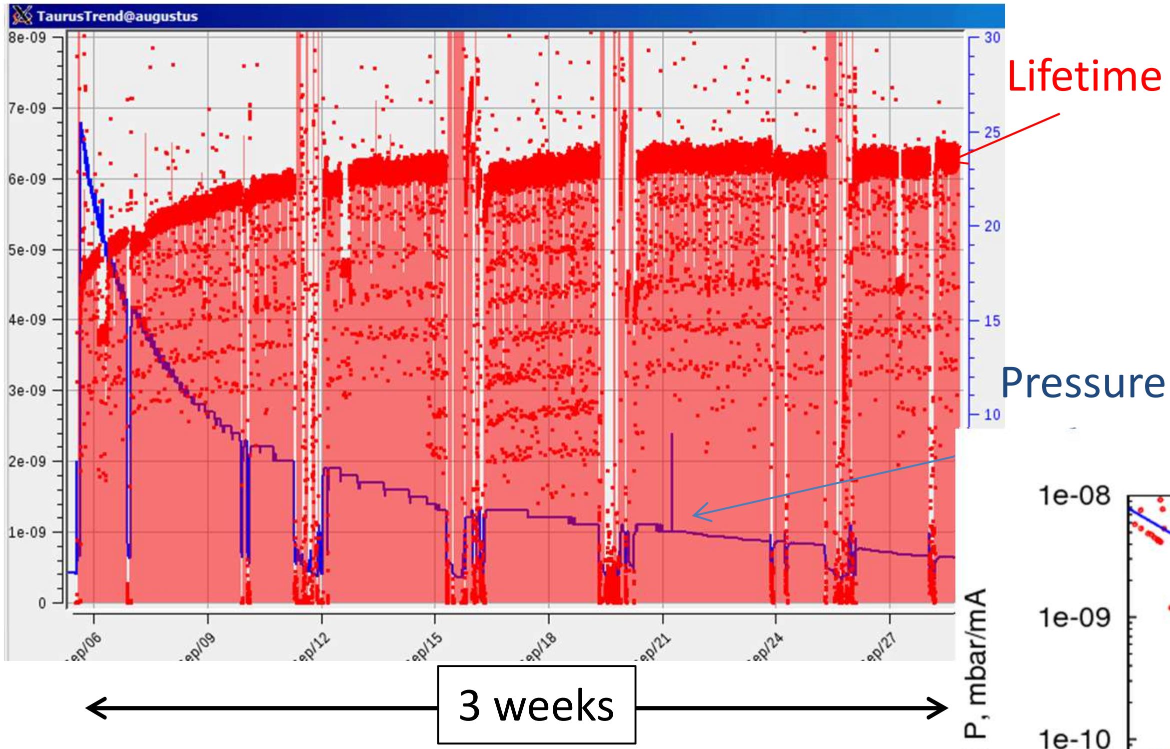


Courtesy of M.Cox and I. Martin (Diamond)

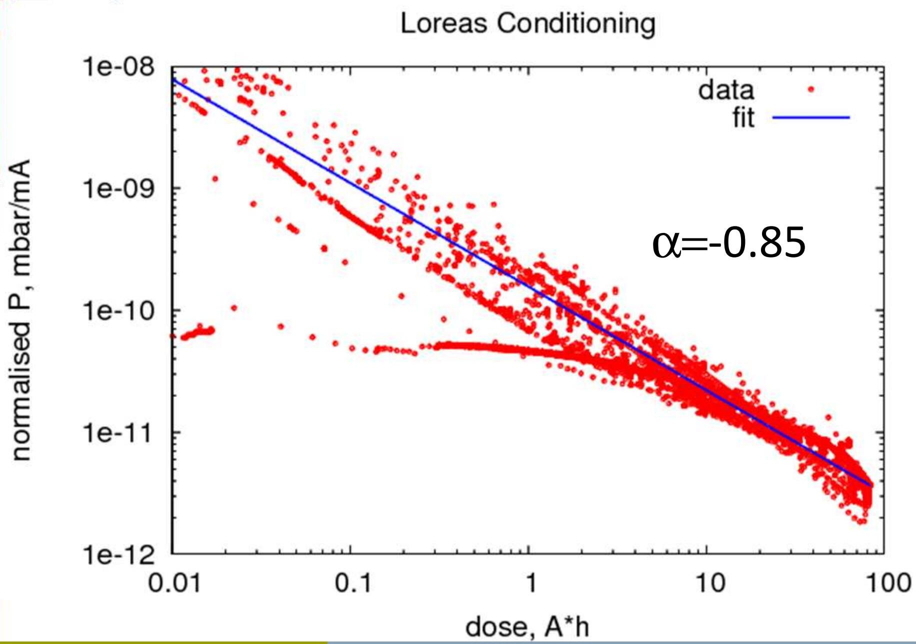


Installation of new components

Example: New Insertion Device (Loreas) @ALBA



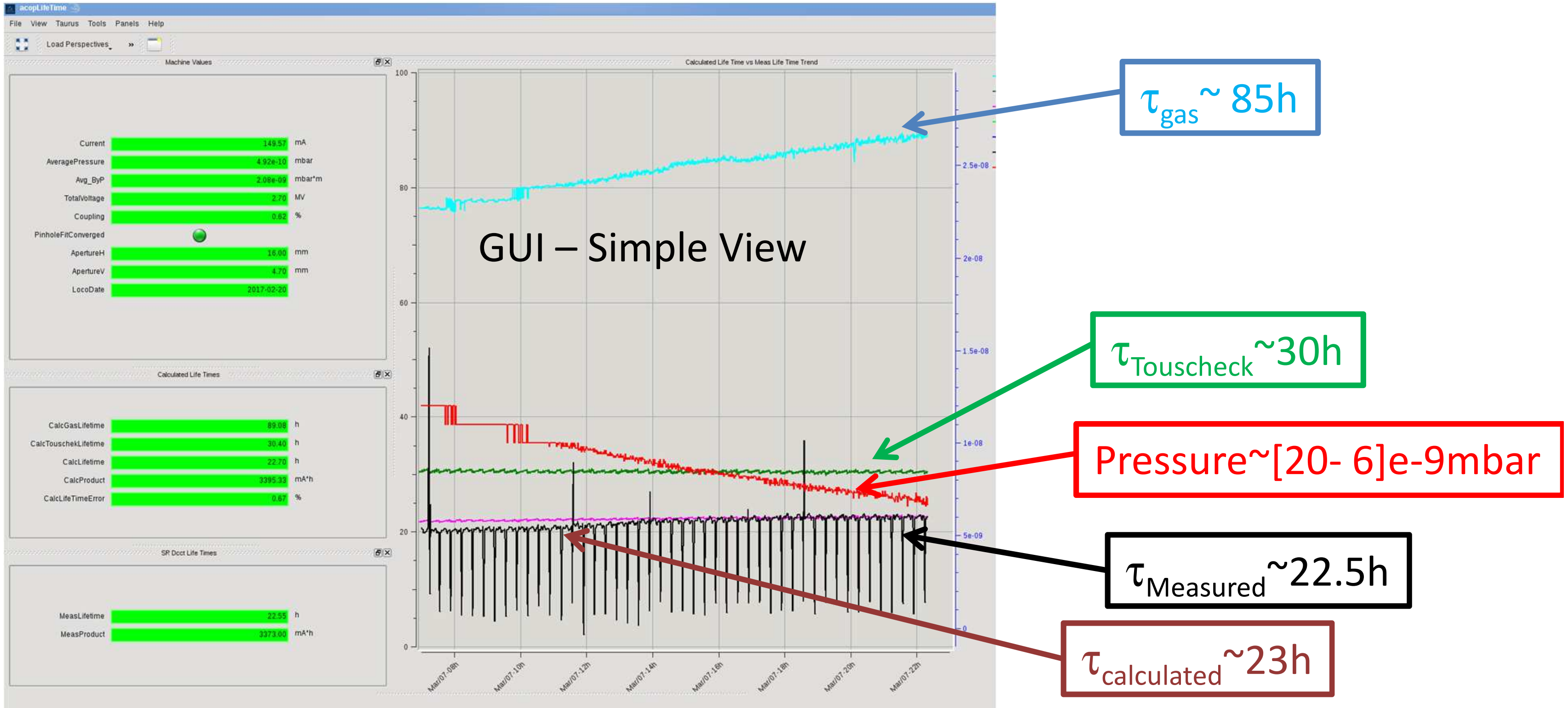
- ~3 weeks to decrease pressure ~1order of magnitude
- ~2 weeks to stabilize lifetime (from 18h to 24h)
- Accumulated Dose: 80A*h



Lifetime Calculator GUI

- Used at ALBA Control Room to crosscheck machine performance
- P@CCG, $\beta_{x,y}$ functions, ε_{xy}, cross sections, etc calculated on-line --> also τ_{gas} & $\tau_{Touscheck}$

Example during conditioning of new vac. chamber



Developed by M.Alvarez

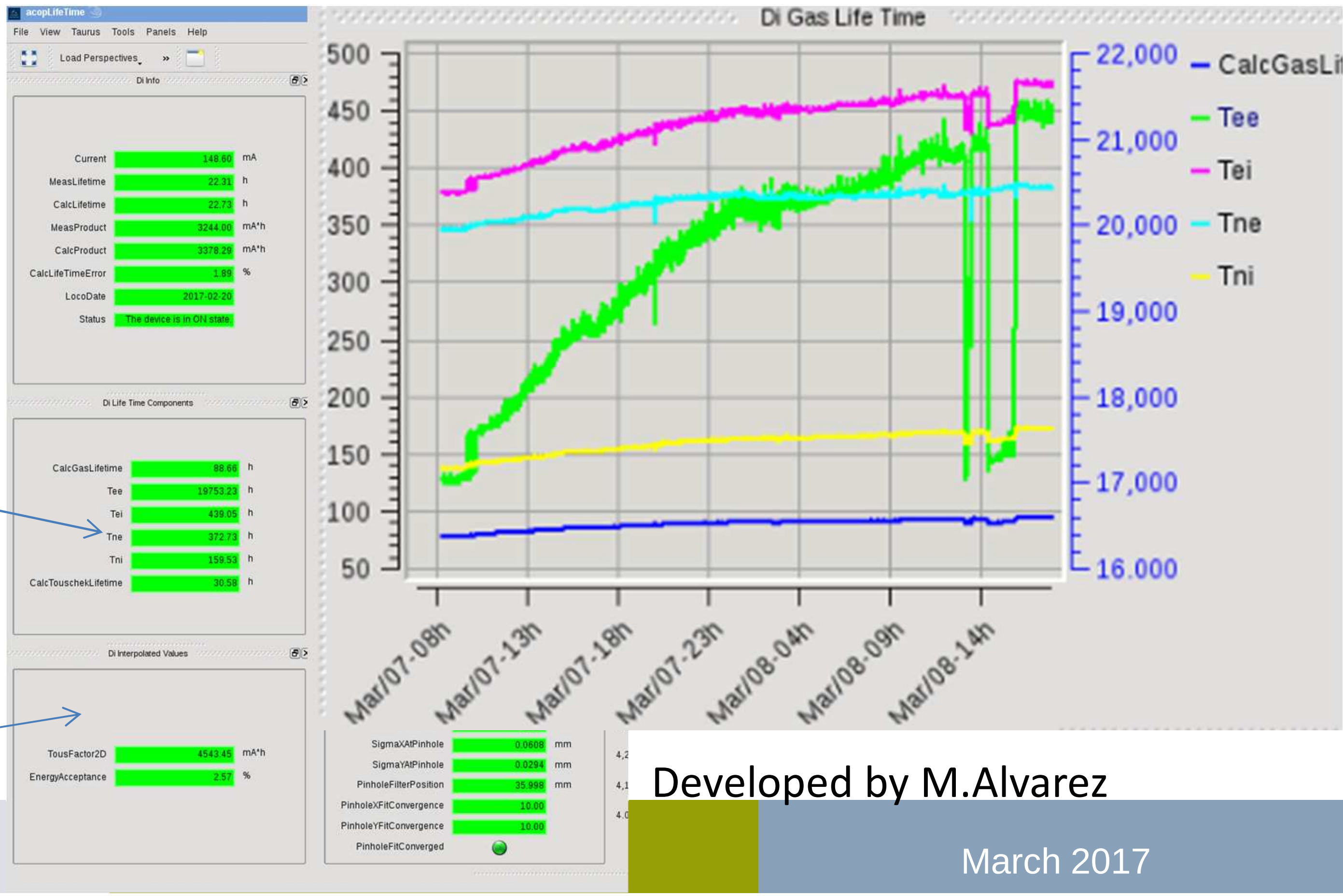
Lifetime Calculator GUI

- Used at ALBA Control Room to crosscheck machine performance
- P@CCG, $\beta_{x,y}$ functions, ε_{xy}, cross sections, etc calculated on-line --> also τ_{gas} & $\tau_{Touscheck}$

GUI – Expert View: allows you to control/measure all lifetime related params

$\tau_{e\text{-}elastic}$
$\tau_{e\text{-}inelastic}$
$\tau_{n\text{-}elastic}$
$\tau_{n\text{-}inelastic}$

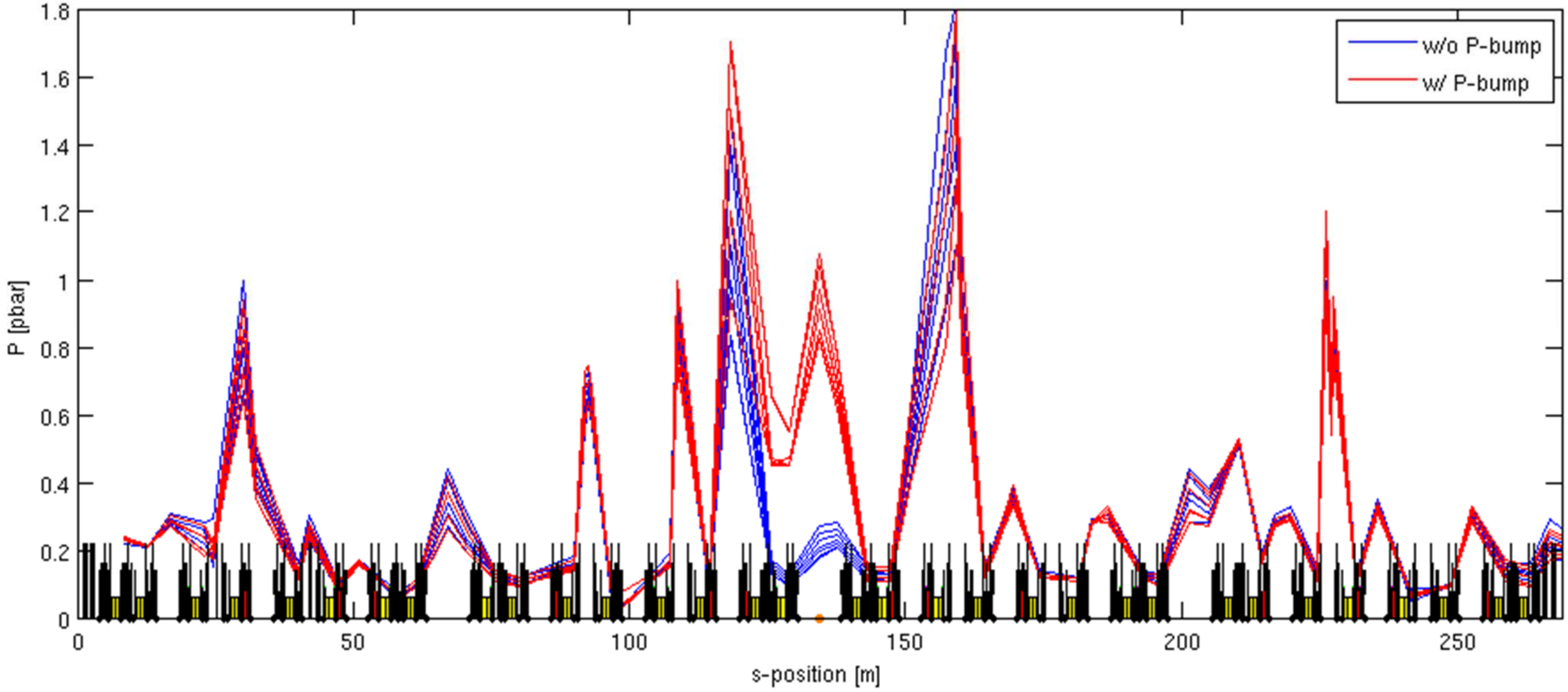
Touscheck params



Developed by M.Alvarez

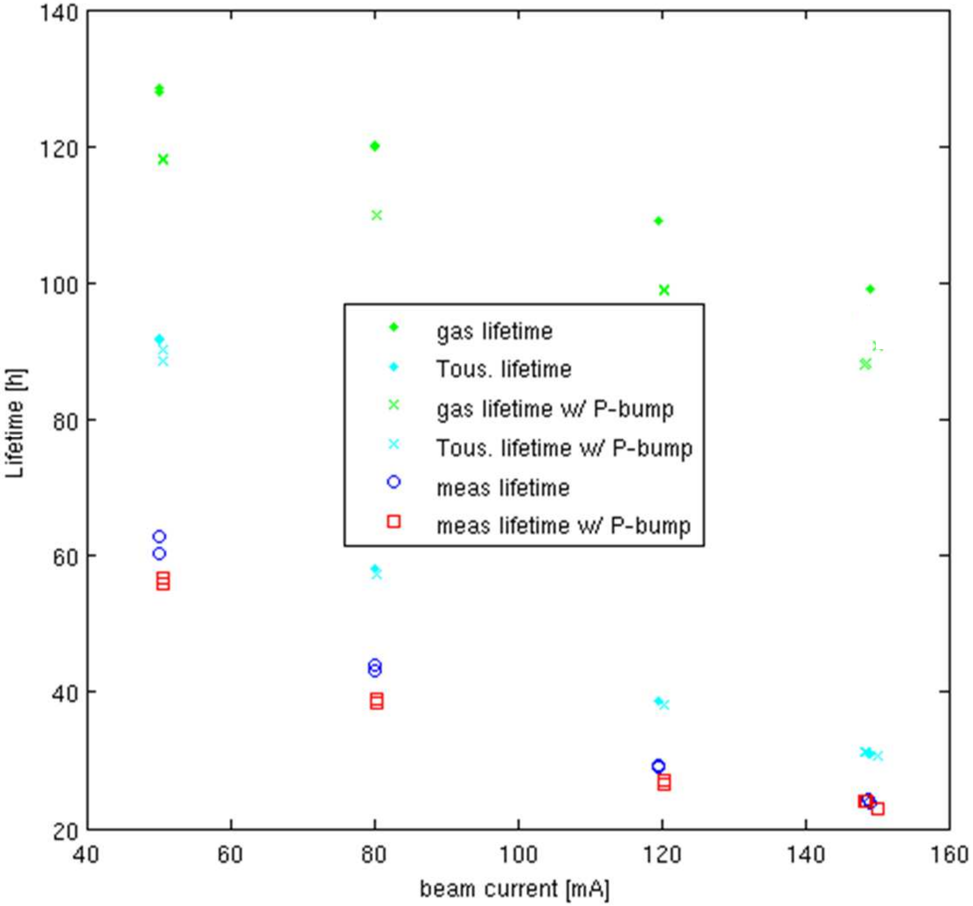
Controlled pressure bump

- Experiment goal: change gas lifetime w.o. varying Touscheck
- Switch off Ion Pumps in one sector (out of 16).
- NEG pumping on → pressure increase ~1 order of magnitude in the Cell



Controlled pressure bump

Lifetime comparison at different beam currents



At 50mA, the lifetime difference is only 10% .

At 150mA, the differences are barely noticeable, since Touscheck lifetime dominates

OUTLINE

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Ion Instabilities in LS

See G. Rumolo and R. Nagaoka talks

- Rest gas ionization produced by e-beam generates ions inside vac. chamber

- Ions are heavy particles and they usually feel only a sequence of attractive kicks from the bunches, which keep them confined near the beam core

- If the ion trapping condition is fulfilled, the ion remains oscillating around the beam

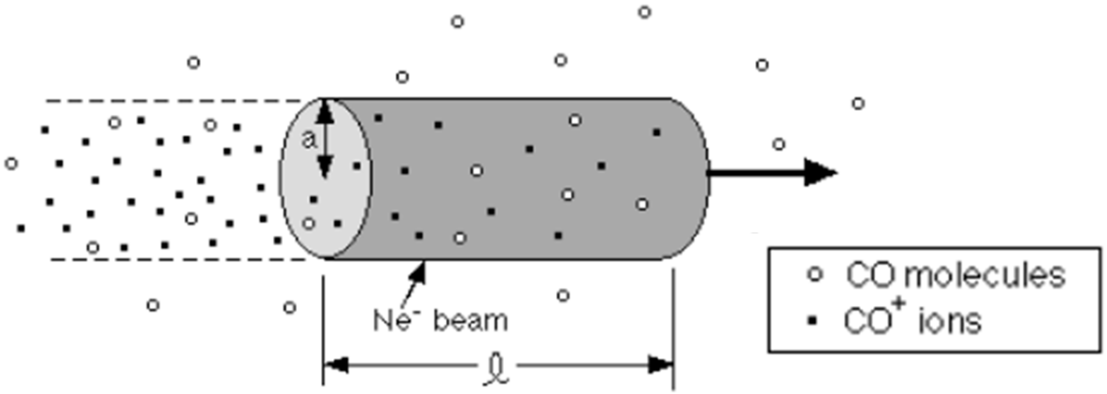
- The Ion Instabilities can be either:
  - "Ion Trapping Instability" (**ITI**): multi-turn ion accumulation that degrades beam quality (cured typically with abort gap)

  - "Fast Beam Ion Instability" (**FBII**), the ion production & accumulation occur within one turn, affecting mainly last bunches in the train.

- Main consequences**: emittance growth, tune shift, pressure rise...**

Ion Instability: ion generation

- Rest gas ionization produced by e-beam generates ions inside vac. chamber



- Scattering ionization (depends on cross section σ_{ion})

$$\lambda = \frac{N_b}{k_B T} \sum_{n=1}^{N} P_n \sigma_n$$

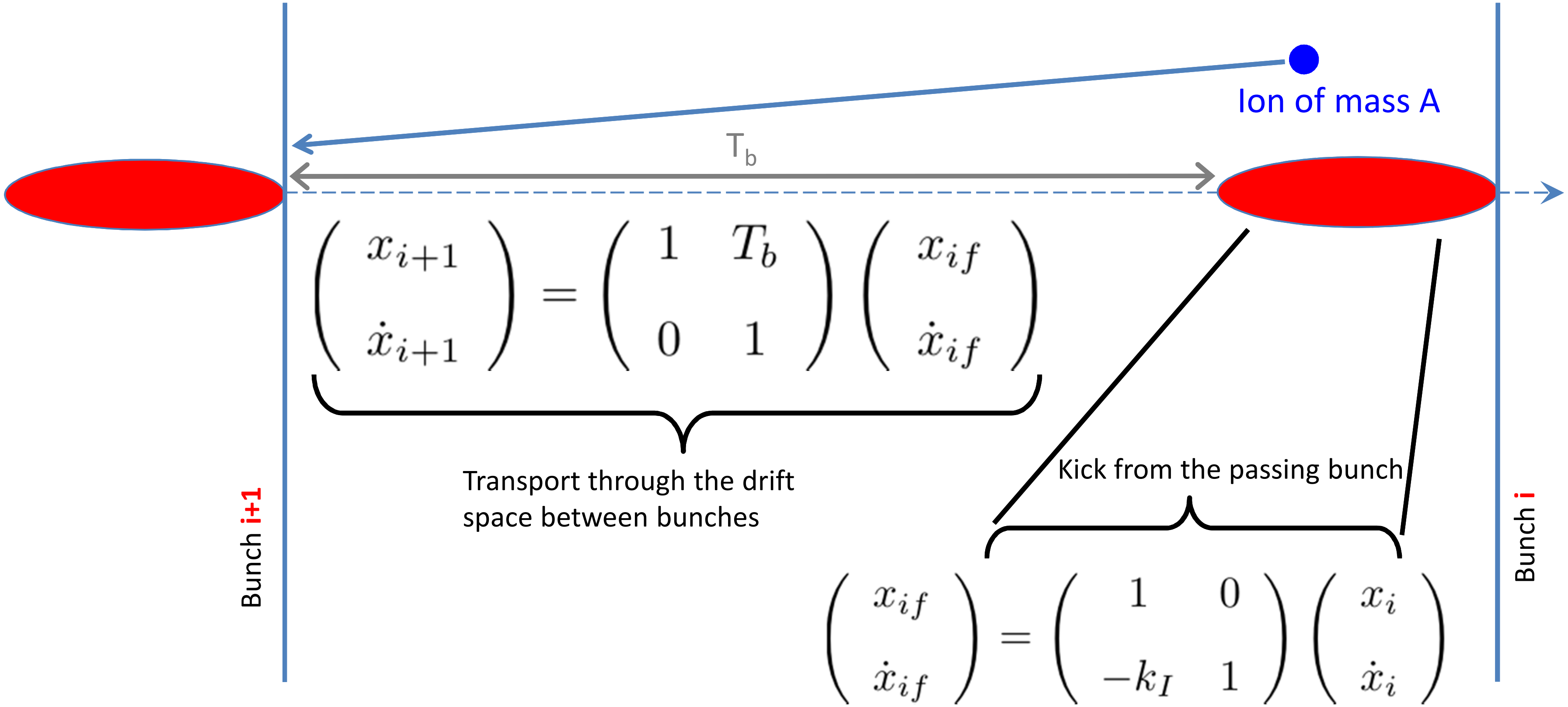
~**20** ions/bunch/m (ALBA, P=1pbar, σ_{ion} = 2MB - CO)

- Field ionization could also happen above a certain threshold, but negligible in current LS – may be relevant for CLIC Linacs

Ion Instability: Trapping Condition

$$\Delta \dot{x} = -\frac{2N_b r_p c}{A\sigma_x(\sigma_x+\sigma_y)}(x- <x>) = -k_I(x- <x>)$$

G. Rumolo -“Two stream Instabilities” – USPAS



$$\begin{pmatrix} x_{i+1} \\ \dot{x}_{i+1} \end{pmatrix} = \begin{pmatrix} 1 & T_b \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x_{if} \\ \dot{x}_{if} \end{pmatrix}$$

$$\begin{pmatrix} x_{if} \\ \dot{x}_{if} \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -k_I & 1 \end{pmatrix} \begin{pmatrix} x_i \\ \dot{x}_i \end{pmatrix}$$

Ion Instability: Trapping Condition

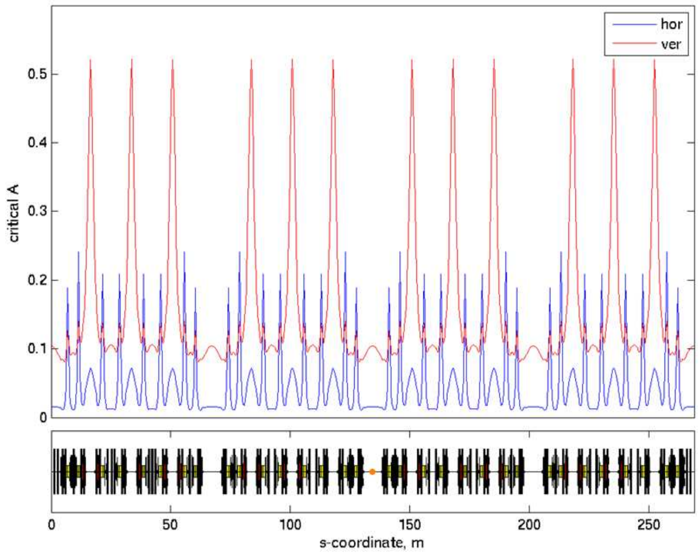
Ion Motion easily expressed in matrix notation:

$$\begin{pmatrix} x_{i+1} \\ \dot{x}_{i+1} \end{pmatrix} = \begin{pmatrix} 1 - k_I T_b & T_b \\ -k_I & 1 \end{pmatrix} \begin{pmatrix} x_i \\ \dot{x}_i \end{pmatrix} = \underline{\mathbf{A}} \cdot \begin{pmatrix} x_i \\ \dot{x}_i \end{pmatrix}$$

Stability if Tr(A) < 2:

$$A_{crit} > \frac{N_B r_p s_B}{2\sigma_y(\sigma_x + \sigma_y)}$$

- Assumed Gaussian beams
- Ions with atomic mass > A_{crit} are trapped!



<u>ALBA @150mA:</u>

- All ions can be trapped!!
- It does not affect ALBA due to use of abort gaps and low pressure (~1e-10mbar)
- Dependence on lattice position through (σ_x, σ_y)

Ion Instability: Trapping Condition

Ion Motion easily expressed in matrix notation:

$$\begin{pmatrix} x_{i+1} \\ \dot{x}_{i+1} \end{pmatrix} = \begin{pmatrix} 1 - k_I T_b & T_b \\ -k_I & 1 \end{pmatrix} \begin{pmatrix} x_i \\ \dot{x}_i \end{pmatrix} = \underline{\mathbf{A}} \cdot \begin{pmatrix} x_i \\ \dot{x}_i \end{pmatrix}$$

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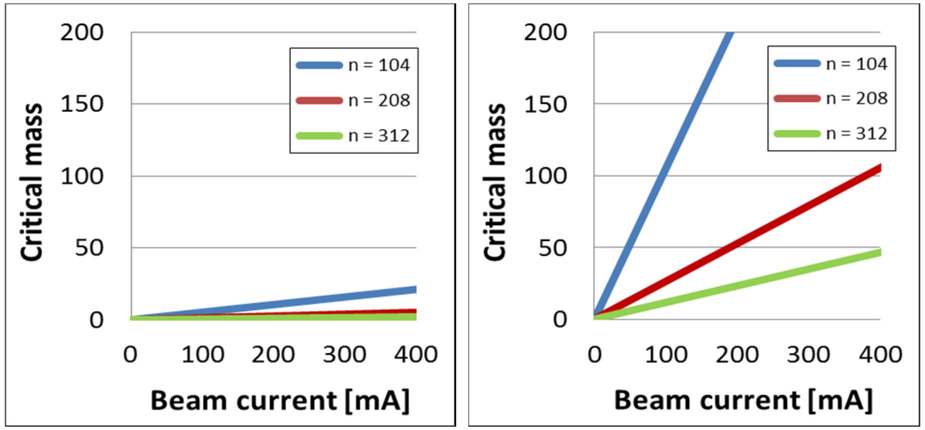


Calculated with ε_x = 4 nm (left) and 0.2 nm (right) with SOLEIL parameters (1% coupling)

R. Nagaoka talk

- For low-e rings, A_{crit} increases

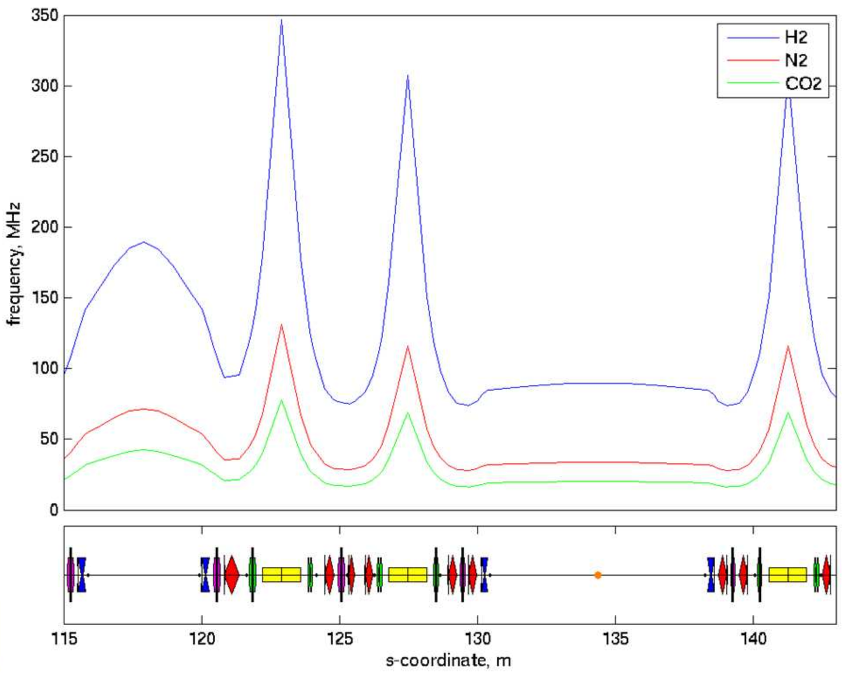
Ion Instability: Osc. Frequency

From $$\Delta\dot{x} = -\frac{2N_b r_p c}{A\sigma_x(\sigma_x+\sigma_y)}(x_i - \langle x\rangle)$$ and $\ddot{x} = \Delta x / T_B$

We get the ion **oscillation frquency**:

$$\omega^2{}_{ion} = \frac{2N_B\, c\, r_p}{A\sigma_y(\sigma_x+\sigma_y)T_B}$$

observable with spectrun analyser



ALBA Case @150mA in one sector:

- Inversely proportional to A
- Between ~[10 – 300MHz]
- Also depends on s-position

Ion Instabilities: tune shift

Induced tune shift due to focusing force:

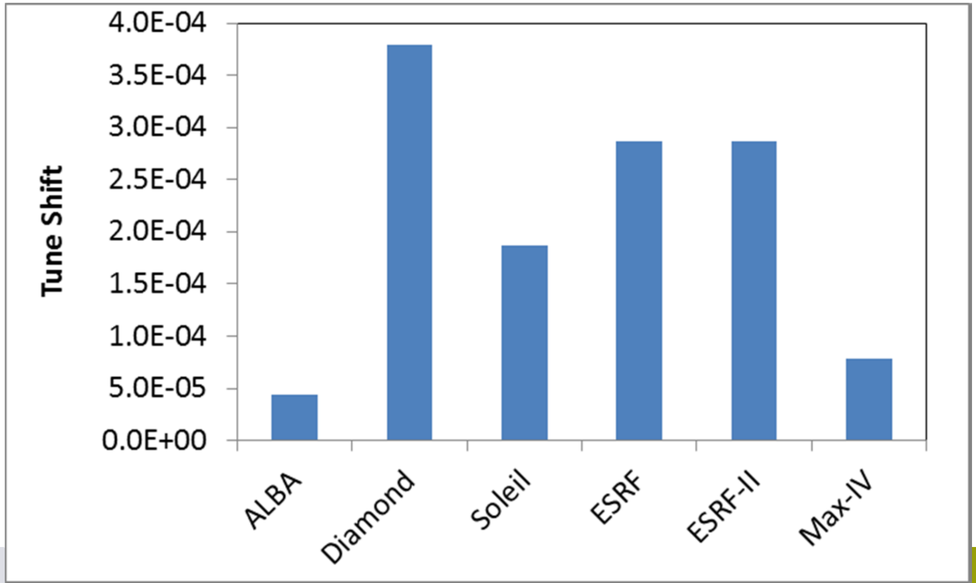
$$\Delta\nu_\beta = +\frac{I_p r_e \eta}{2\pi e c (\beta_c)^3 \gamma B_f} \oint \frac{\beta_y ds}{\sigma_y(\sigma_x + \sigma_y)}$$

An easier simplification from above equation is:

$$\Delta\nu_y = \frac{r_e \lambda_{ion} C < \beta_y >}{4\pi\gamma\sigma_y(\sigma_x + \sigma_y)}$$

Note:

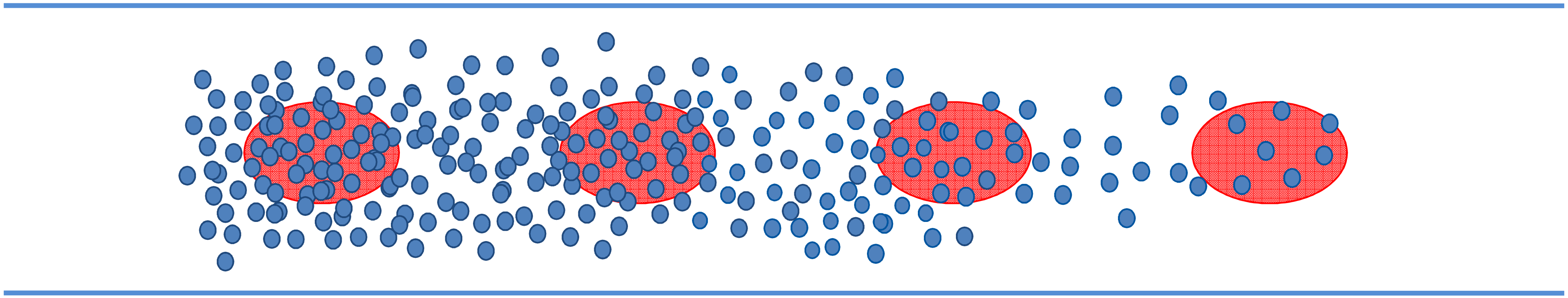
- positive tune shift
- For FBII, λ_{ion} depends on the bunch #, so the tune shift depends on the bunch 3



CO ions; P=1pbar; σ_{ion} = 2MB
Nominal operation conditions

Tune shift small, but measurable

Fast Beam Ion Instability - FBII



→ The ions accumulate along one bunch train

→ Head and tail of the train are coupled through the ions

→ Coupled motion between ions & e-beam: ions “keep memory” of the offset of the generating bunch and transfer this information to the following bunches.

→ The driven oscillation is expected to be at a main frequency related to the ion oscillation frequency.

See analytical models at:

Raubenheimer *et al.* Phys. Rev. E 52, 5, 5487,
Stupakov *et al.* Phys. Rev. E 52, 5, 5499

Fast Beam Ion Instability - FBII

Analytical instability models* allow to estimate rise times:

$$\frac{1}{\tau_e} \approx \frac{1}{3}\sqrt{\frac{2}{3}}\frac{c}{\Delta\omega_i/\omega_i}\beta_y k_y$$

With K_y the focusing strength

$$k_y = \frac{\lambda_i r_e}{\gamma\sigma_y(\sigma_x+\sigma_y)}$$

- This gives rise times ~**2us** range at ALBA, although coherence effects along the ring can increase this rise times by 1-2 orders of magnitude
- Each case needs a careful analysis

- Computer simulation codes (FASTION ad PyHEADTAIL**) can be used to carefully calculate these rise times.

*Raubenheimer *et al.* Phys. Rev. E 52, 5, 5487,
Stupakov *et al.* Phys. Rev. E 52, 5, 5499

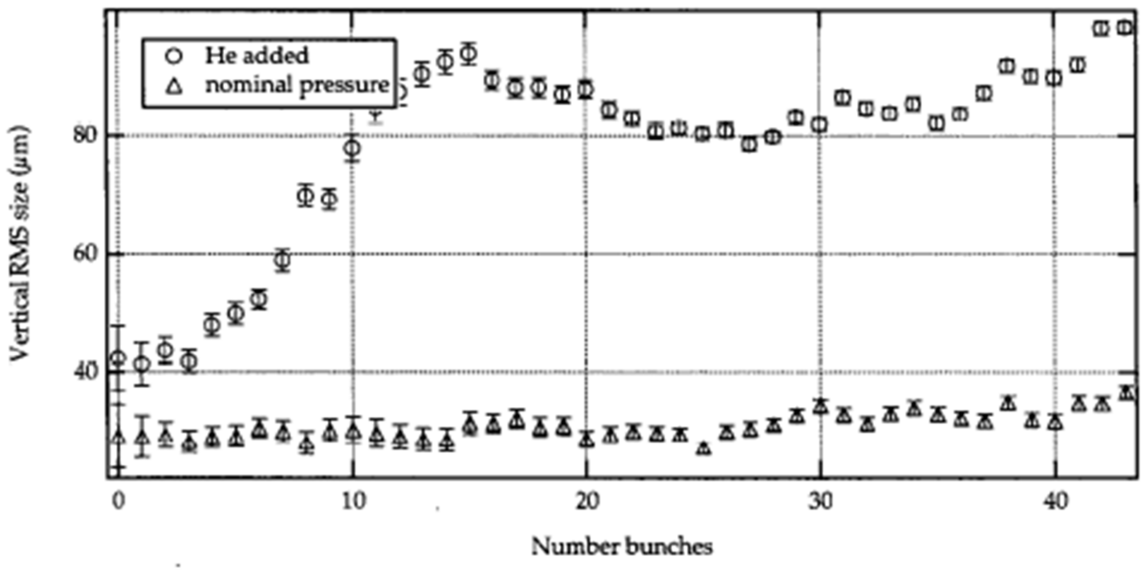
**L.Mether, “Numerical model of FBII”, Proc. of HB2016
A.Chaterjee et al, PRST-AB 18 064402 (2015)

Ion Instabilities Observations

- **Fast Beam Ion Instabilities** observed in LS are produced artificially induced by injecting gas into the vacuum chamber
- See examples at **ALS & CESR**

ALS experiment*:

- all Ion Pumps off
- Inject He: avg P from 0.25 to 80 nTorr



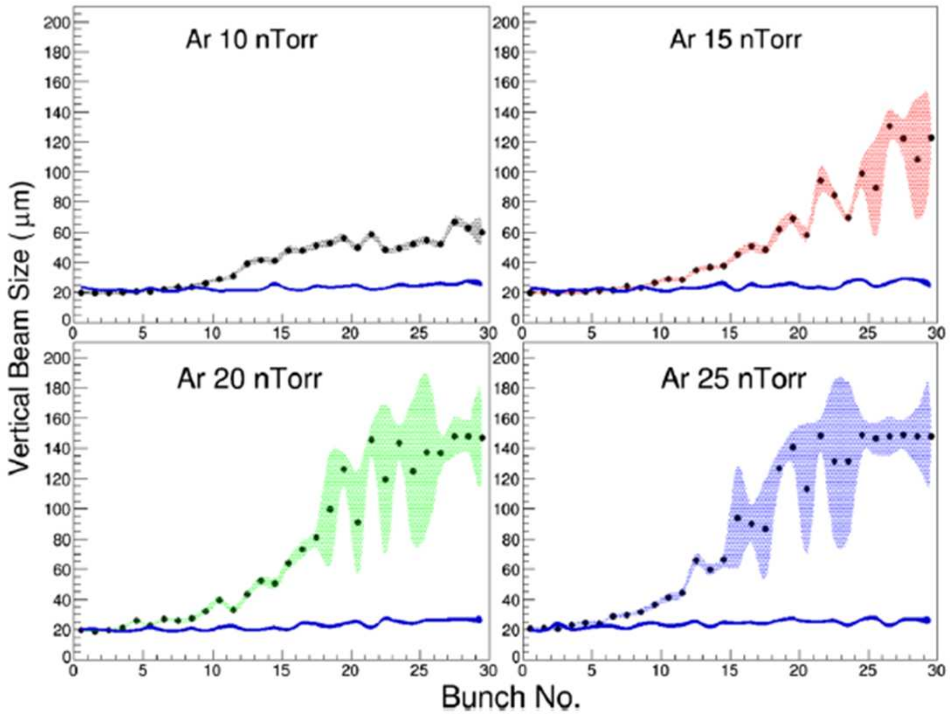
*J.Byrd et al, PRL 79, 1 (1997)

Ion Instabilities Observations

- **Fast Beam Ion Instabilities** observed in LS are produced artificially induced by injecting gas into the vacuum chamber
- See examples at **ALS & CESR**

CESR experiment*:

- Localized pressure bump of ~10m
- Inject Ar and Kr: from 1 to 25 nTorr



- Beam Size observation
- BBB feedback can damp instability
- Observations match well with simulations using FASTION

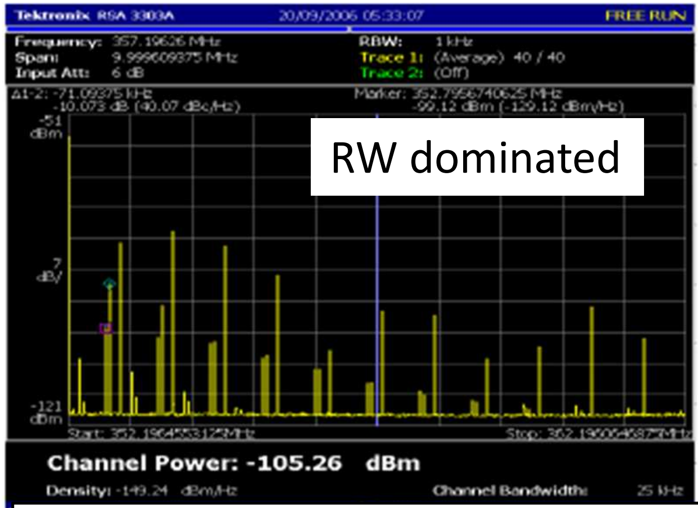
*A.Chaterjee et al, PRST-AB 18 064402 (2015)

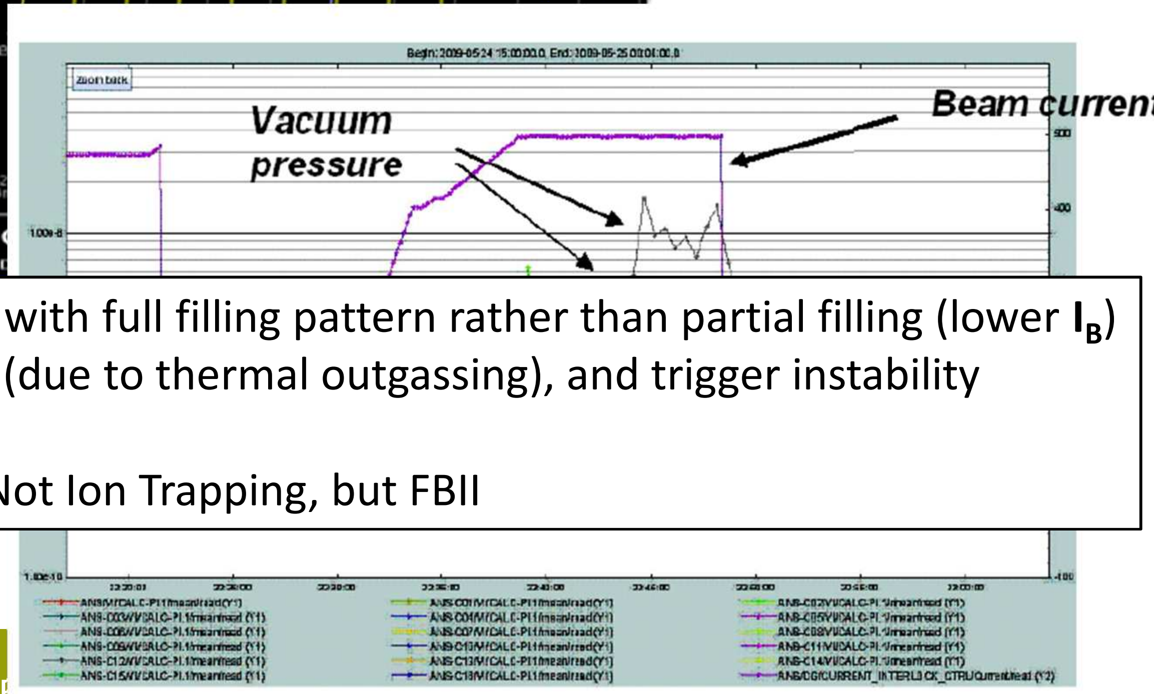
Ion Instabilities Observations

Beam Spectra and Pressure Rise in Soleil

R. Nagaoka, IPAC'10

- Soleil is so far the only LS affected by ions during operation
- The beam spectrum for ions dominated instabilities show a distinct pattern wrt usual RW spectrum





To prevent this instability, Soleil runs with full filling pattern rather than partial filling (lower I_B)
This prevents pressure to rise (due to thermal outgassing), and trigger instability

➔ Not Ion Trapping, but FBII

Ion Instabilities Observations

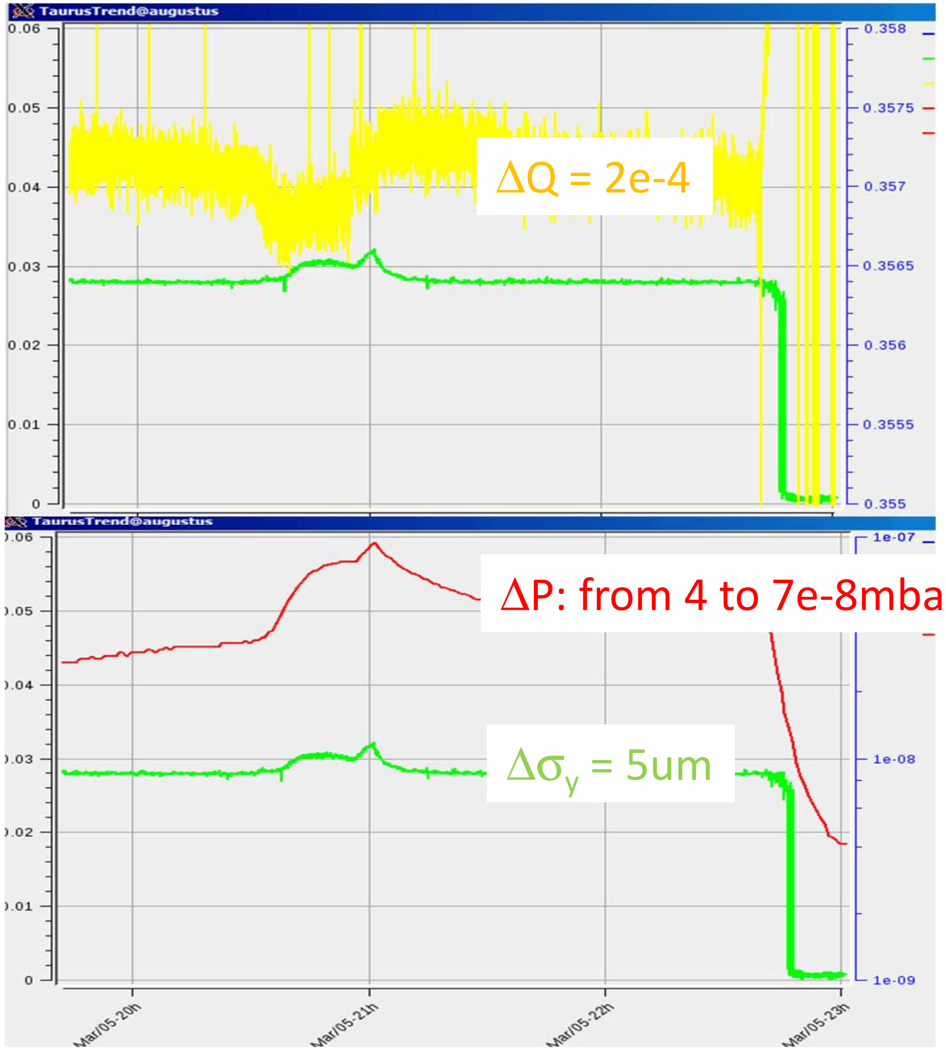
Installation of CLIC SL Kicker @ALBA

(Data from 6/3/2017)

While conditioning the new vacuum chamber, injecting from **125mA** to **135mA** produced a:

-pressure rise: ~3e-8mbar
-beam blow up (by 20%)
-tune shift of 2e-4
-BBB feedback could not damp it

Compatible with ion instabilities in this case produced by larger atomic masses (see next)



Ion Instabilities Observations

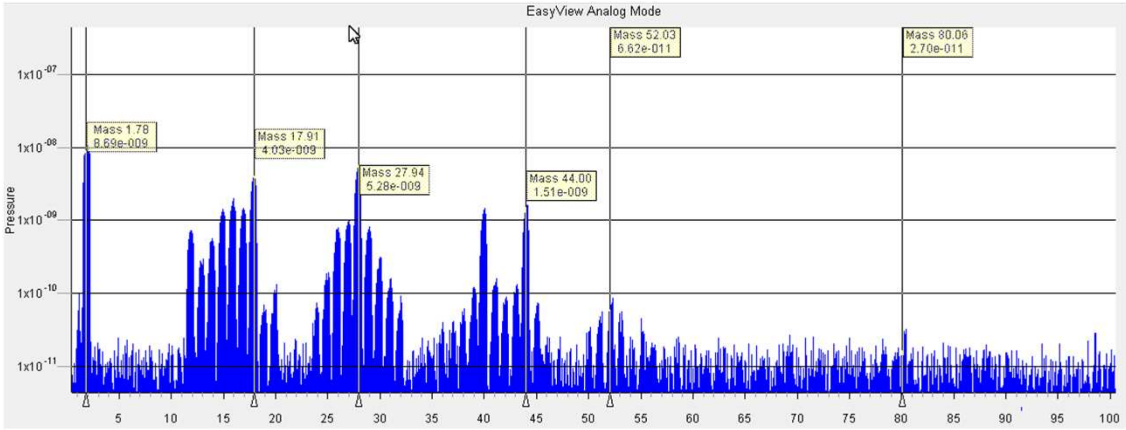
Installation of CLIC SL Kicker @ALBA

(Data from 6/3/2017)

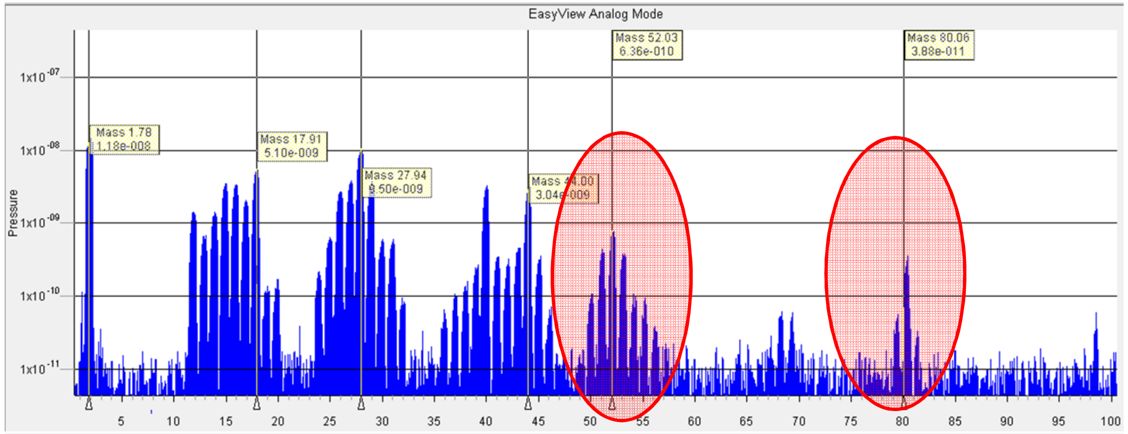
- RGA data showed peaks at A=52 and A=80, likely due to desorption produced by Macor rings

- CLIC SL removed to guarantee operation

125 mA

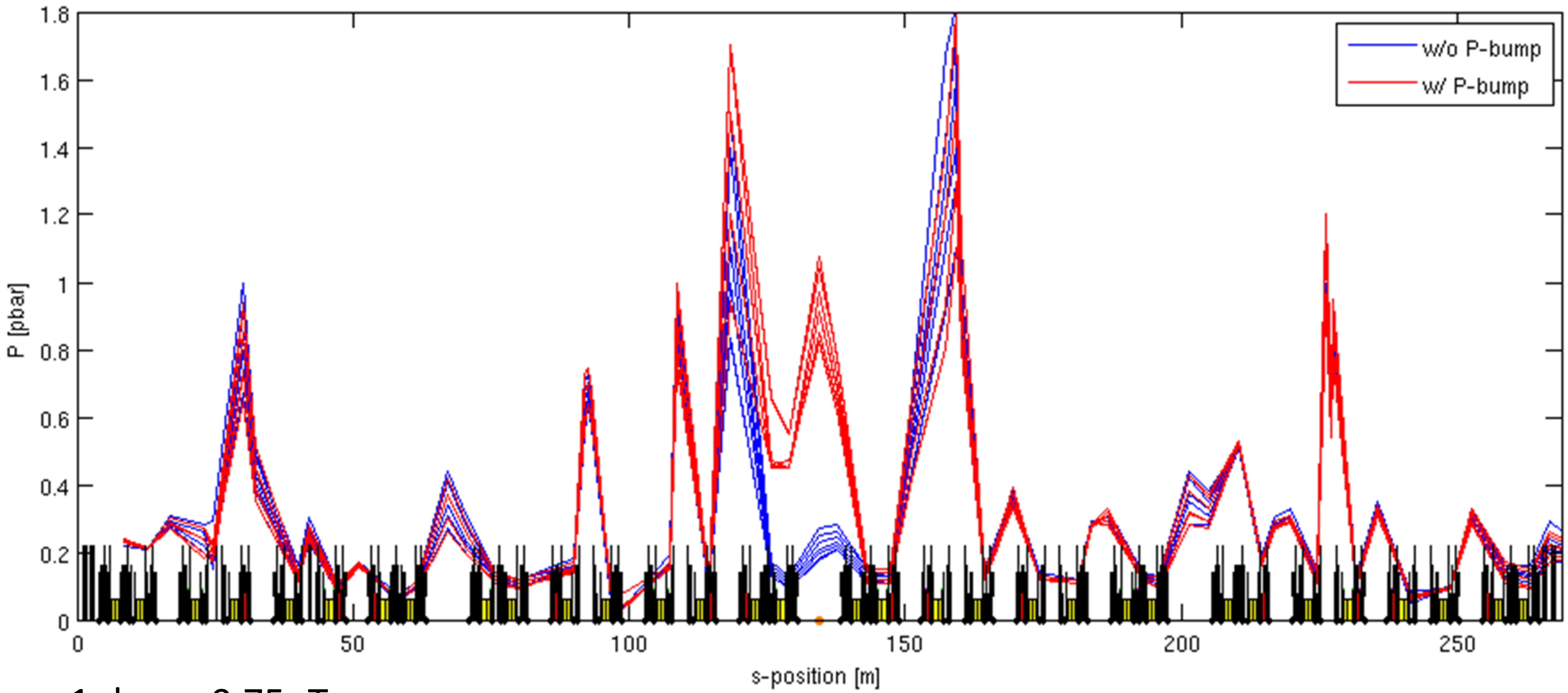


135 mA



Controlled pressure bump

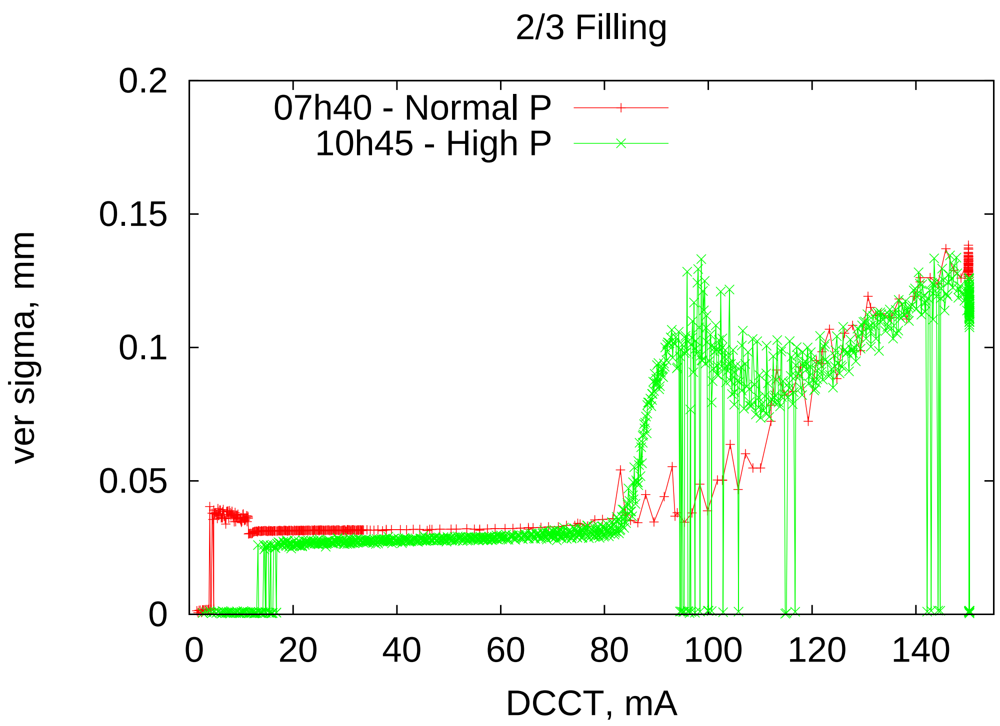
- Switch off Ion Pumps in one sector (out of 16).
- NEG pumping on → pressure increase ~1 order of magnitude in the Cell
- Check instability thresholds w. & w.o. pressure bumps



1pbar = 0.75nTorr

Controlled pressure bump

➔ Beam size increase with increasing current with & w.o. pressure bump



- Xi = (1,2), threshold ~80mA for both cases
- But for normal pressure, the emittance increase is much violent. Co-existance of RW and Ions?
- At ~120mA, beam size follows the same trend as the case with normal P (larger Nb, ions "untrapped"?)
- Further studies going-on

OUTLINE

1. Beam Lifetime
   a) Theoretical Equations
   b) Impact on current Light Sources

2. Ion Instabilities
   a) Analytical Equations
   b) Observations in Light Sources

3. Conclusions

CONCLUSIONS

As for the lifetime…

- Lifetime in LS is limited by Touscheck effect for machines with doses >100 A*h
- Gas lifetime (elastic and inelastic) ~100h, while Touscheck lifetime ~20h.
- Gas lifetime only relevant in commissioning periods, or after installation of new components
- As a rule of thumb, need in ~100A*h to recover P<1e-9mbar (0.75nTorr)

CONCLUSIONS

As for the ion instabilities…

- Ion trapping condition is easily fulfill in LS. However, observations of ion instabilities are rare due to a very good vacuum conditions (Pavg < 5e-10mbar) .
- Ion instabilities are only relevant in commissioning periods or after installation of new components in the vacuum chamber
- FBII have only seen in artificially bad vacuum conditions (injecting Ar gas) and/or switching off Ion Pumps to bring P>10nTorr
- Ion instabilities may co-exist with other instabilities (RW) , and active feedback may effectively damp them (CESR) or not (Soleil)
- Soleil is (so far) the only machine whose operation is limited by ion instabilities (FBII).
- Simulation codes exist (FASTION & PyHeadtail), but more benchmarking is appreciated

Acknowledgements

Many colleagues from ALBA and other labs contributed to this talk:

M. Alvarez, T. Guenzel, Z. Marti, R. Monge (ALBA)

I.Martin, M.Cox (Diamond)
N.Carmignani (ESRF)
X. Nuel (Soleil)
J. Sundberg (Max-IV)
G. Rumolo (CERN)

Extra slides

http://inspirehep.net/record/846682/files/PhysRevSTAB.12.pdf
S.C. Leeman, Phys. Rev. ST Accel. Beams 12, 120701 (2009)

TABLE VII. Contributions to the total MAX IV 3 GeV storage-ring lifetime τ. The results have been calculated for a "worst-case scenario": four PMDWs and ten IVUs are installed in the storage ring while the total applied rf voltage is 1.5 MV which corresponds to an rf acceptance of only $\delta_{rf} = 4.0\%$.

	τ [h]
Elastic gas scattering	25.4
Inelastic gas scattering	53.1
Touschek scattering (with Landau cavities)	25.5
Total	10.3

MACOR®

Machinable Glass Ceramic

- is MACHINABLE with ordinary metal working tools
- allows FAST TURNAROUND, no post firing required
- holds TIGHT TOLERANCES, up to .0005"
- withstands HIGH TEMPERATURE, up to 1000°C (no load)
- is CLEAN, no outgasing and zero porosity

Composition

MACOR Machinable Glass Ceramic is a white, odorless, porcelain-like (in appearance) material composed of approximately 55% fluorophlogopite mica and 45% borosilicate glass. It has no known toxic effects; however, the dust created in machining can be an irritant. This irritation can be avoided by good housekeeping and appropriate machining techniques. The material contains the following compounds:

	Approximate Weight %
Silicon - SiO_2	46%
Magnesium - MgO	17%
Aluminum - Al_2O_3	16%
Potassium - K_2O	10%
Boron - B_2O_3	7%
Fluorine - F	4%

Fast Beam Ion Instability - FBII

- Analytical model available*
  - Instability rise time equations, with & w.o. ion freq. spread along s

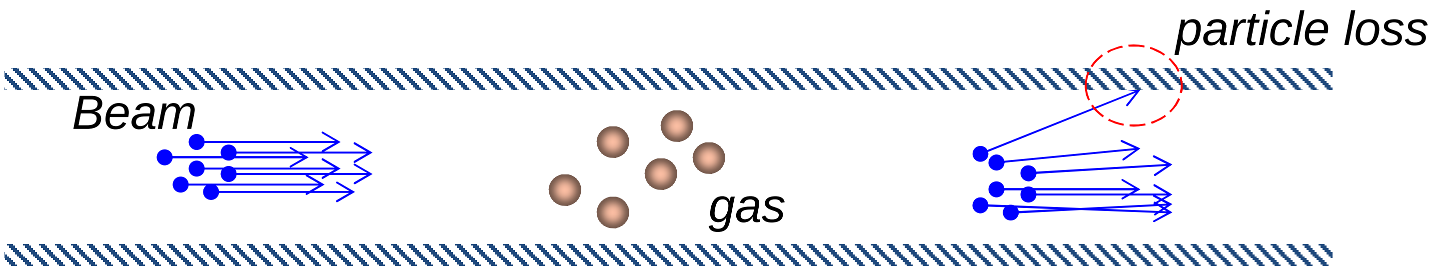
$$\frac{1}{\tau_F} = \frac{4d\sigma_{ion}\beta_y N_b^{3/2} n_b^2 r_p^{1/2} r_e s_b^{1/2} c}{3\sqrt{3}\gamma A^{1/2}\sigma_y^{3/2}(\sigma_x+\sigma_y)^{3/2}}$$

Lower ε = faster instability

Raubenheimer *et al.* Phys. Rev. E 52, 5, 5487,
Stupakov *et al.* Phys. Rev. E 52, 5, 5499

Elastic Gas Scattering

Deflections caused by the **electromagnetic force** of the residual gas atoms. It can be due either by electrons or the nuclei (but the e- part is usually negligible for current LS)



Simplified Eqs:

$$\sigma_{el}(s) = 2\pi \frac{\beta_y(s)}{J_{y,\max}} \left(\frac{Z r_0}{\gamma} \right)^2$$

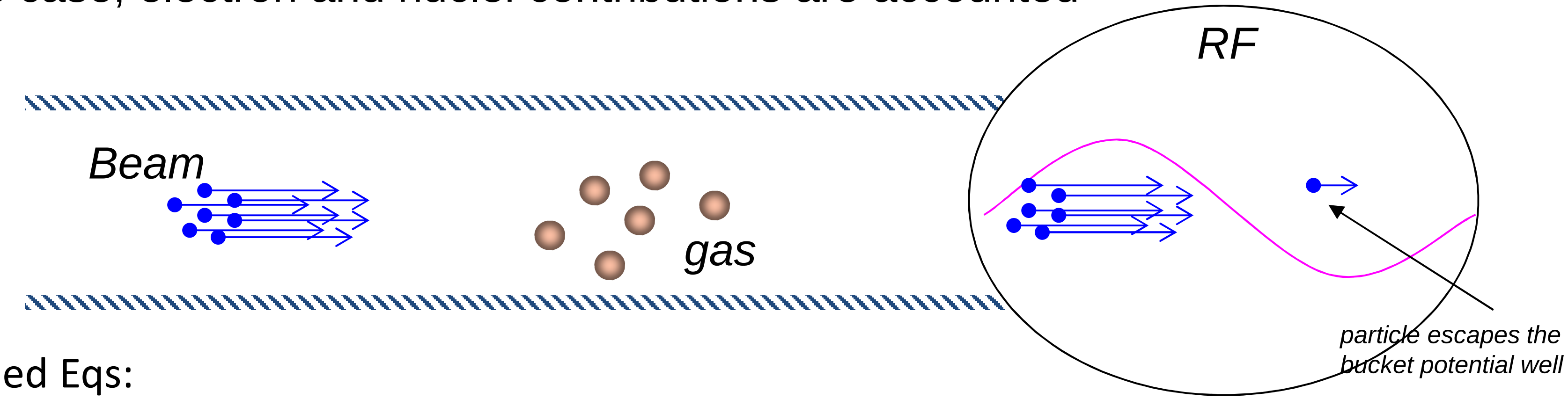
$$\tau_{el}^{-1} = \frac{c\beta}{kT} \langle P(s) \sigma_{el}(s) \rangle$$

Basic dependencies:

1. Number of residual particles (pressure): P↑→τ↓
2. Particle Charge: Z↑→τ↓
3. Beam energy: γ↑ →τ↑
4. Beta function. β↑ →τ↓
5. Beam size: σ_y↑→τ↑

Inelastic Gas Scattering

Energy loss caused by **radiation emission (mostly)** at the vicinity of the gas atoms.
In this case, electron and nuclei contributions are accounted



Simplified Eqs:

$$\sigma_{in}(s) = 4\alpha r_0^2 \left\{ \left[\frac{4}{3}\left(\delta_{acc}(s) - \ln(\delta_{acc}(s))\right) + \frac{\delta_{acc}^2(s)}{2} \right] F(Z) + \frac{Z(Z+1)}{9}\left(\delta_{acc}(s) - \ln(\delta_{acc}(s))\right) \right\}$$

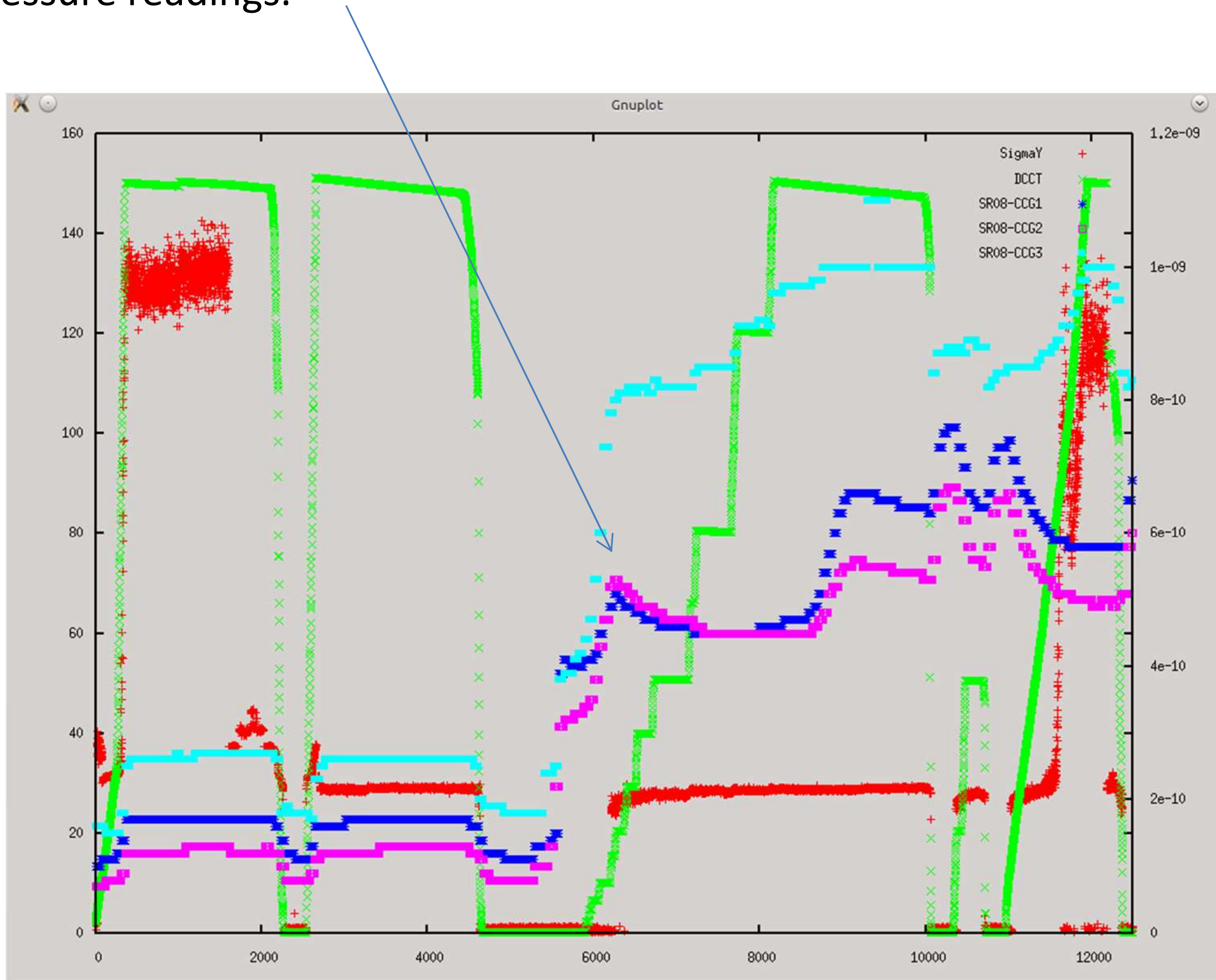
$$F(Z) = Z^2 \ln\left(\frac{183}{Z^{1/3}}\right) + Z \ln\left(\frac{1194}{Z^{1/3}}\right)$$

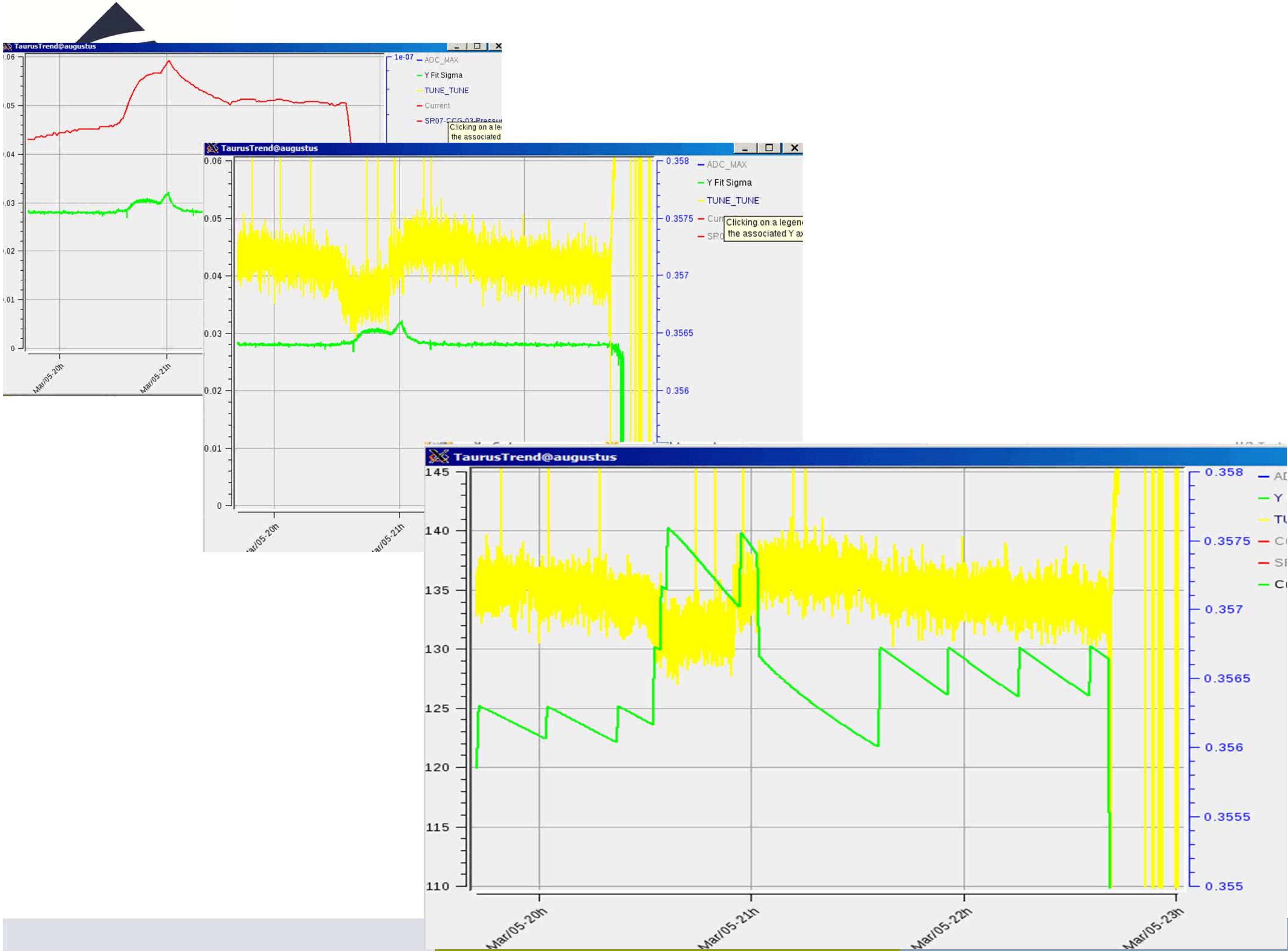
$$\tau_{in}^{-1} = \frac{c\beta}{kT}\left\langle P(s)\sigma_{in}(s) \right\rangle$$

Basic dependencies:

1. Number of rest gas atoms: $P \uparrow \rightarrow \tau \downarrow$
2. Charge of every particle: $Z \uparrow \rightarrow \tau \downarrow$
3. RF acceptance. $\delta_{acc} \uparrow \rightarrow \tau \uparrow$

Only SR08-CCG3 behaves “as expected” in the whole range.
For CCG1 and 2, after switching off certain pumps, there is a point in which both decrease even though the current increases: this (may) mean that after a certain P, you start the formation of a significant amount of gas ionization (or e-) which affects the pressure readings.




TaurusTrend@augustus
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120
115
110
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Mar/05-22h
Mar/05-23h