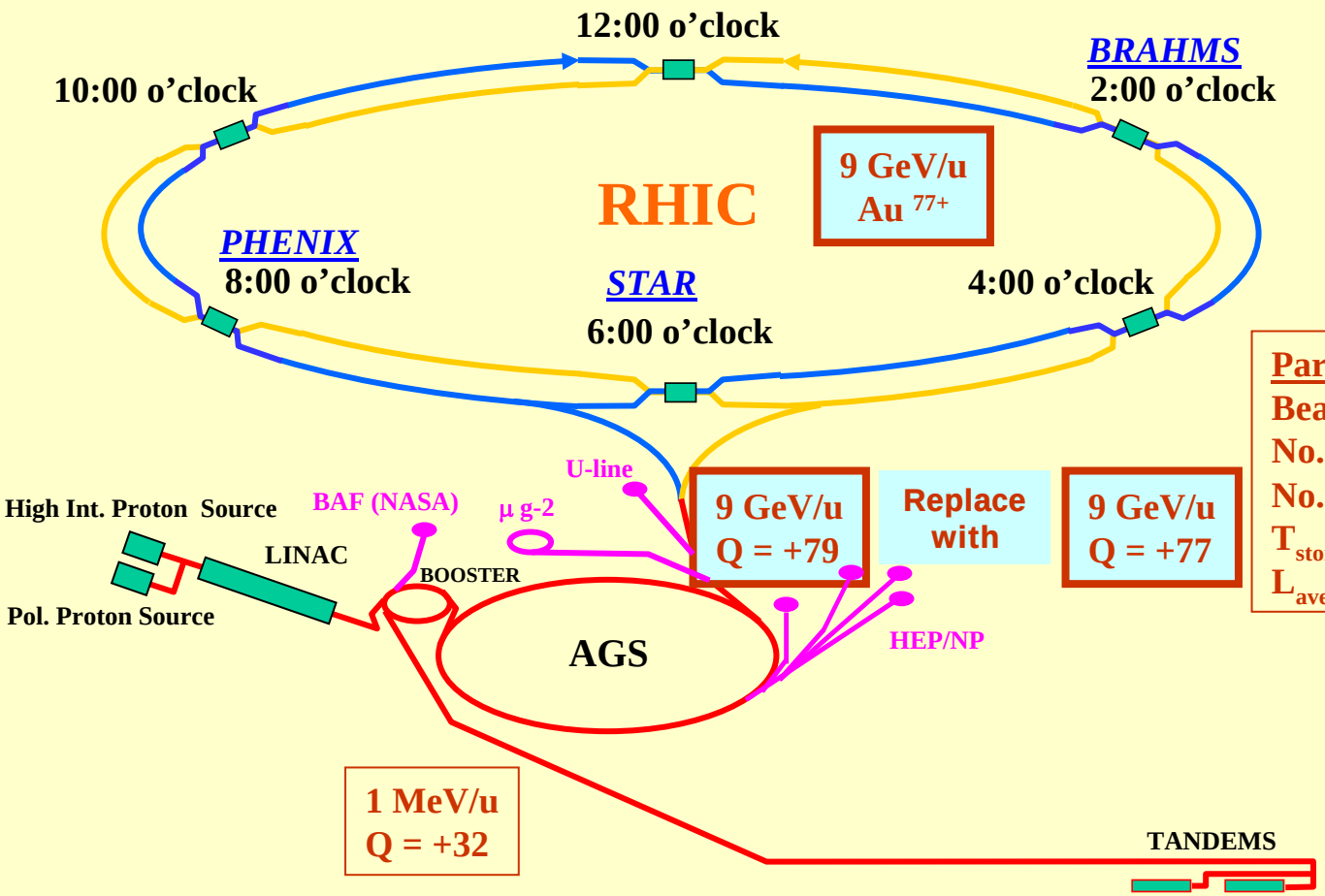
Report from experiments: Au^{77+} in RHIC

Dejan Trbojevic

- **Introduction**
  - **Remainder: injection of Au^{79+} in RHIC and Au^{77+} extraction in AGS.**
  - **Area of interest: IBS or beam gas interactions could be possible cooling mechanisms, interest for collisions between not-fully stripped ions in RHIC ?, acceleration of not fully stripped heavy ions?, ...**
- **Few introductory remarks:**
  - **Basics of the intra-beam scattering.**
  - **The Barat-Fano-Lichten theory of electron promotion during ion collisions. Heavy-ion collisions, electron promotion, quasi-molecular orbital.**
- **Previous proposals: Prof. Kurt Kilian-Julich, M.W. Krasny-University et Marie Curie-Paris, ...**
- **Details of the experiment proposal and participants.**
- **Possible future developments.**

Introduction: Present situation for gold run



Parameters in the next run?:

Beam Energy = 100 GeV/u

No. Bunches = 110?

No. Ions /Bunch = 1-2 × 10^9

T_{store} = 10 hours

L_{ave} = 2 × 10^{26} cm^{-2} sec^{-1}

Introduction:

- **Au^{77+} extraction in AGS, stripping @ U-line F2 flag, ATR line tuned for Au^{79+} and injection of in RHIC.**

The rest mass of fully stripped gold $m_{Au}c^2$ =183.4333180 GeV

$$B_{RHIC}\rho_{RHIC} = \frac{A\beta_o\gamma_o}{Zec} m_{amu} c^2 = \frac{197}{79}\frac{\beta_o\gamma_o}{ec} m_{amu} c^2$$

$$B_{AGS}\rho_{AGS} = \frac{A\beta_o\gamma_o}{Zec} m_{amu} c^2 = \frac{197}{77}\frac{\beta_o\gamma_o}{ec} m_{amu} c^2$$

$$\frac{\beta_1\gamma_1}{\beta_o\gamma_o} = \frac{79}{77}$$

$$\frac{B_{AGS_1}\rho_{AGS_1}}{B_{AGS_o}\rho_{AGS_o}} = \frac{\beta_1\gamma_1}{\beta_o\gamma_o} = \frac{79}{77}$$

- if we fix the **B**ρ in RHIC and ATR (AGS to RHIC transfer line) only the U – line part of

Phase space cooling by inelastic scattering

K. K. ECOOL 9/84 in Karlsruhe DPG 3/86 in Heidelberg
ECOOL 5/90 in Padua (Proceedings R. Calabrese + L. Tecchio)

- **Intra beam scattering of partially ionized ions**
  Ionization, charge transfer, elastic, inelastic

$A^{\xi+}+A^{\xi+} \rightarrow$	$A^{\xi+}+A^{(\xi+1)+}+e^-$	only when $\varepsilon_{coll} \gg \varepsilon_I$	losses
	$A^{(\xi+1)+}+{}^{(\xi-1)+}$	threshold $< \varepsilon_I$	
	$A^{\xi+}+A^{\xi+}$	mixes $\Delta p_{x,y,l}$	no losses
	$A^{\xi+}+A^{*\xi+}$	$\sigma_{inel} \sim 10^{-16} cm^2$?	

Idea: ⇒ inelastic & photon emission gives cooling

- **Intra beam scattering can excite electron shells without charge changes (without beam loss)**
- **Subsequent photon emission reduces finally the relative energy (→ beam temperature)**
- **Relative movement of ions in beam is damped**

⇒ **Avoid processes which change charges !**
$\varepsilon_{collision} < \varepsilon_I$

⇒ **ensure high enough collision energy** ε_{coll}
$\varepsilon_{excit} < \varepsilon_{collision}$

My special interest is here:

$Au^{77+} + Au^{77+} \rightarrow Au^{77+} + Au^{77+*}$

Symmetric intra beam collisions

*c. m. momentum p**

$$p^* \Rightarrow \begin{cases} \Delta p_L \; 1/\gamma \\ \Delta p_T = p_0 \, \theta_{x,y} = p_0 \, (\varepsilon_{x,y} / \pi \beta_{x,y})^{1/2} \end{cases}$$

c. m. collision energy ε

$\sigma_{ion-ion} = \sigma(\varepsilon)$

$$\varepsilon = (p^*)^2 / M = 1/M \left[(\Delta p_L / \gamma)^2 + (p_0^2 / \pi) \, (\varepsilon_x / \beta^*_x + \varepsilon_y / \beta^*_y) \right]$$

M.W. Krasny

LPNHE, University Pierre et Marie Curie, Paris

- **COMPETITION TO eRHIC? : <u>Initial idea:</u> provide parasitic electron beam at hadronic colliders.**

- **Leave one (or two) K-shell electrons and try to store partially stripped ions in the storage rings – get a parasitic ep (eA) collider**

  (e.g. $s^{1/2}_{LHC}$(ep)= 200 GeV)

- ***Embark on dedicated studies*** *- preliminary results - they need to be confirmed by accelerator physicists! and tests!!*

Basics of the intra-beam scattering

Intrabeam scattering or multiple scattering is a Coulomb scattering within a bunch. Due to dispersion a change of energy always causes a change in the betatron amplitude – coupling between the transverse and longitudinal motion.

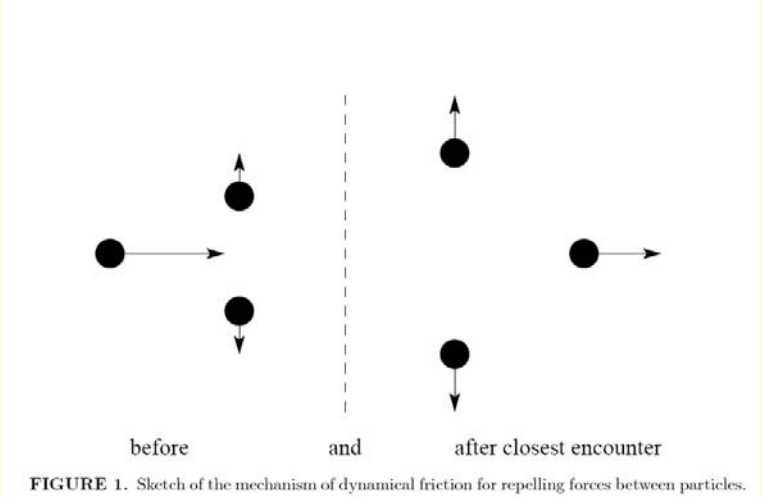
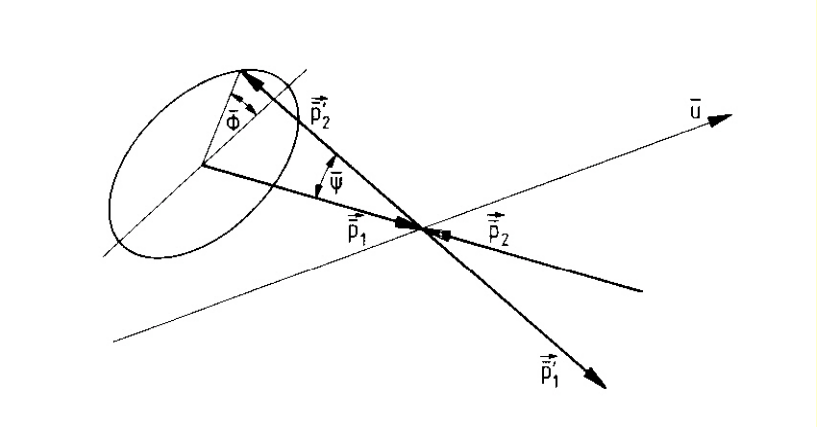


FIGURE 1. Sketch of the mechanism of dynamical friction for repelling forces between particles.



A change the frame of reference:

$$p^*_{x,y,z} \simeq \begin{cases} \Delta p_z/\gamma & \text{(longitudinal)} \\ \Delta p_{x,y} = p_0\,\theta_{x,y} = p_0\sqrt{\epsilon_{x,y}/\pi\beta^*_{x,y}} & \text{(transversal)} \end{cases}$$

The intrabeam collision energy which is relevant in all cross section

$$E_c = \frac{(p^*)^2}{M} \approx \frac{1}{M}\left[\frac{(\Delta p_z)^2}{\gamma^2} + \frac{p_0^2}{\pi}\left(\frac{\epsilon_x}{\beta^*_x} + \frac{\epsilon_y}{\beta^*_y}\right)\right]$$

The longitudinal heating [A. V. Fedotov]:

$$\tau_\parallel^{-1} = \frac{1}{\sigma_p^2}\frac{d\sigma_p^2}{dt} = \frac{r_i^2 c N_i \Lambda}{8\beta^3\gamma^3\epsilon_x^{3/2}\langle\beta_\perp^{1/2}\rangle\sqrt{\pi/2}\,\sigma_s\sigma_p^2}.$$

The transverse growth rate expressed through the longitudinal growth rate by dispersion function:

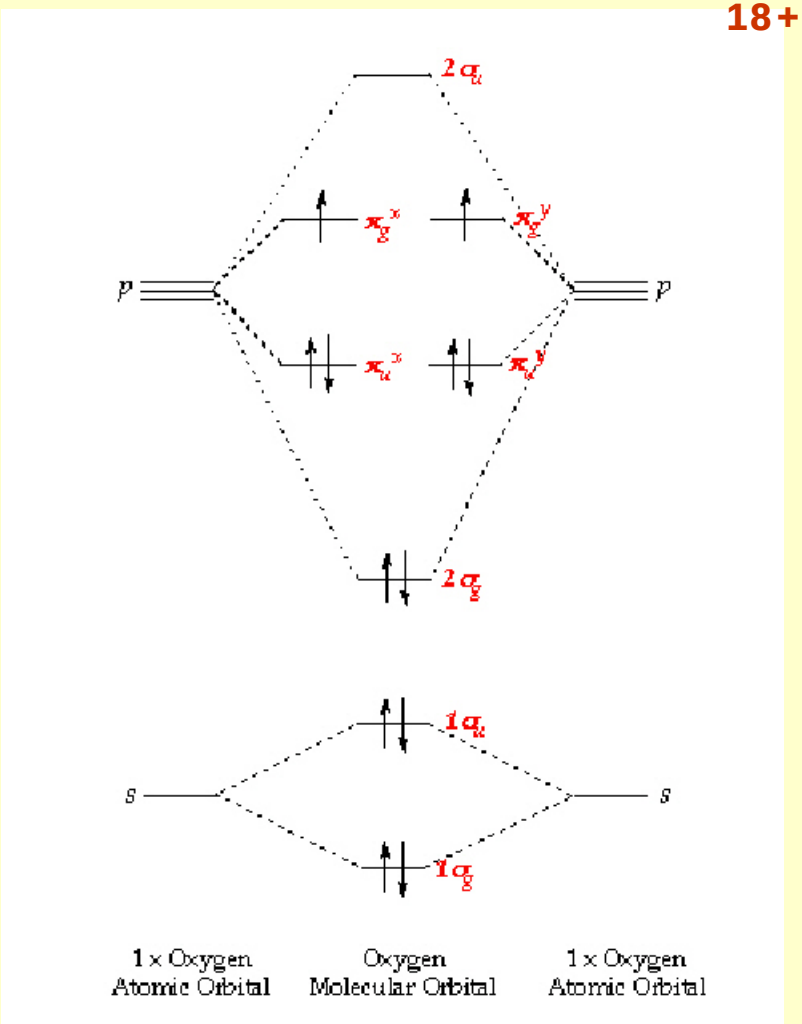
$$\tau_\perp^{-1} = \frac{\sigma_p^2}{\epsilon_x}\left\langle\frac{D_x^2 + (D'_x\beta_x + \alpha_x D_x)^2}{\beta_x}\right\rangle\tau_\parallel^{-1} = \frac{\sigma_p^2}{\epsilon_x}\langle H\rangle\tau_\parallel^{-1}$$

Velocity number from Alexei:

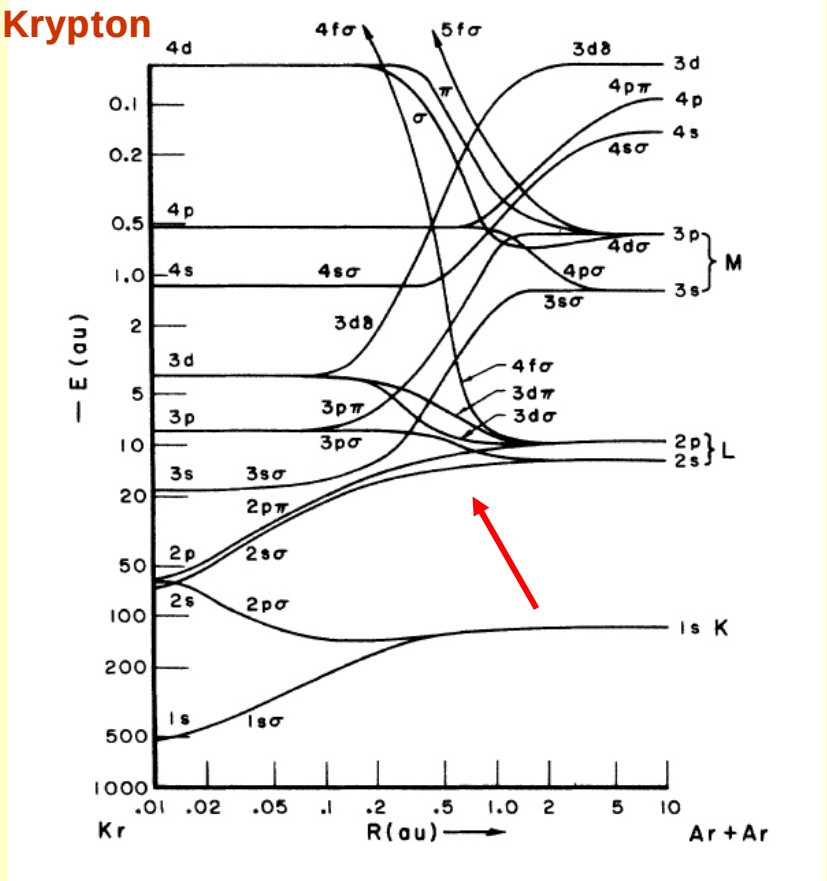
$v_{\text{ion velocity x,y}} = 3\times10^5$ m/s,

$\beta = 1\times10^{-3}$ $E_{kin} = 91.843$ keV !!!

The Barat-Fano-Lichten ELECTRON-PROMOTION theory



18+18=36 Krypton



The extent of the ionization observed and, more specifically, the rapid decrease of the low-Q^* peak as r_0 enters the critical range, show that the level crossing leads with high probability to the "promotion" of electrons to outer shells, as the nuclei approach. It will be shown in a detailed paper that numerous

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North-Holland, Amsterdam

150–350 keV ARGON AND NEON INDUCED X-RAY EMISSION FROM A Mo TARGET *

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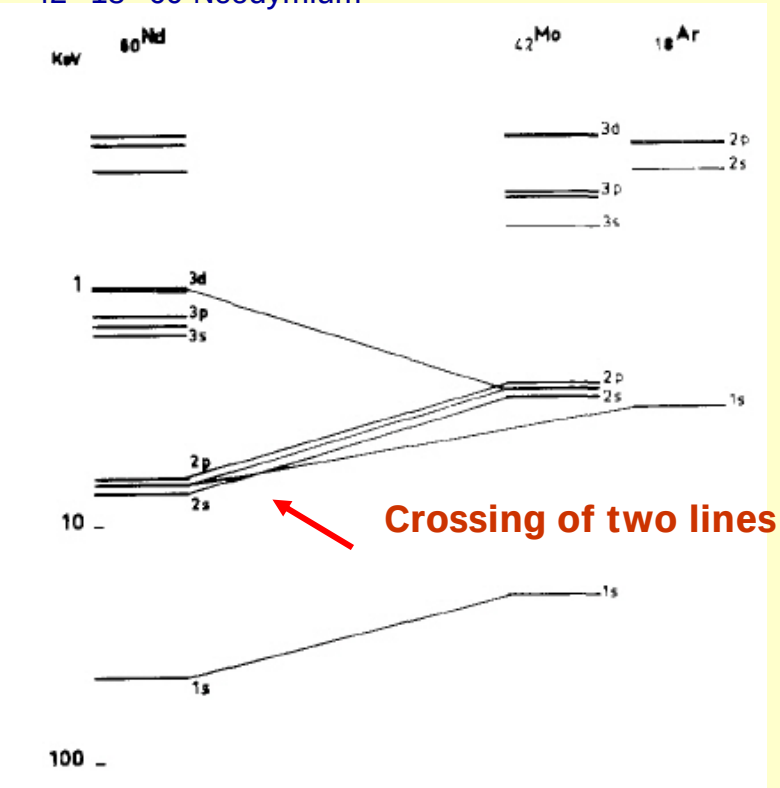
Received 8 September 1986 and in revised form 17 January 1987

42+18=60 Neodymium



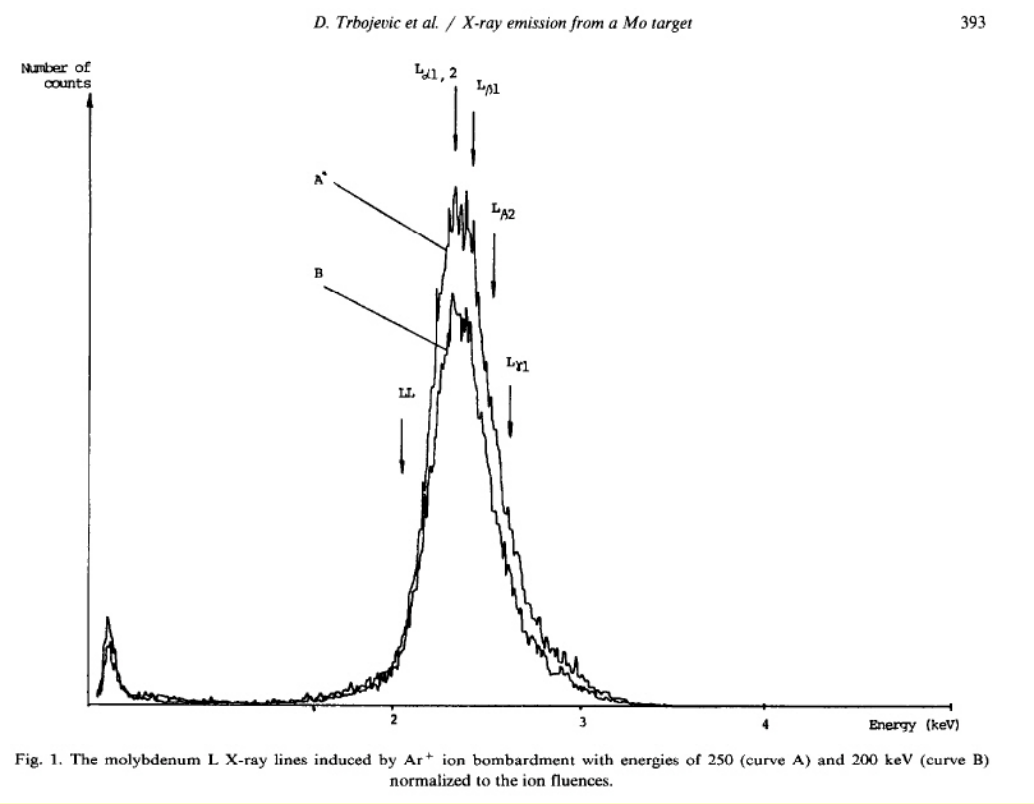


Fig. 1. The molybdenum L X-ray lines induced by Ar^+ ion bombardment with energies of 250 (curve A) and 200 keV (curve B) normalized to the ion fluences.

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K-X-RAY SPECTRUM OF THE Pb + Pb QUASIMOLECULES*

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Received 9 November 1977

We present ab initio calculations of the quasimolecular K-X-ray spectrum from the Pb + Pb system, where both the K-hole amplitude and the radiation amplitude is calculated in first order perturbation theory A comparison with the background radiation like NNB, SEB and γ-decay of excited nuclei shows that the molecular X-rays should be measurable up to X-ray energies corresponding to the characteristic K-line of the united superheavy atom

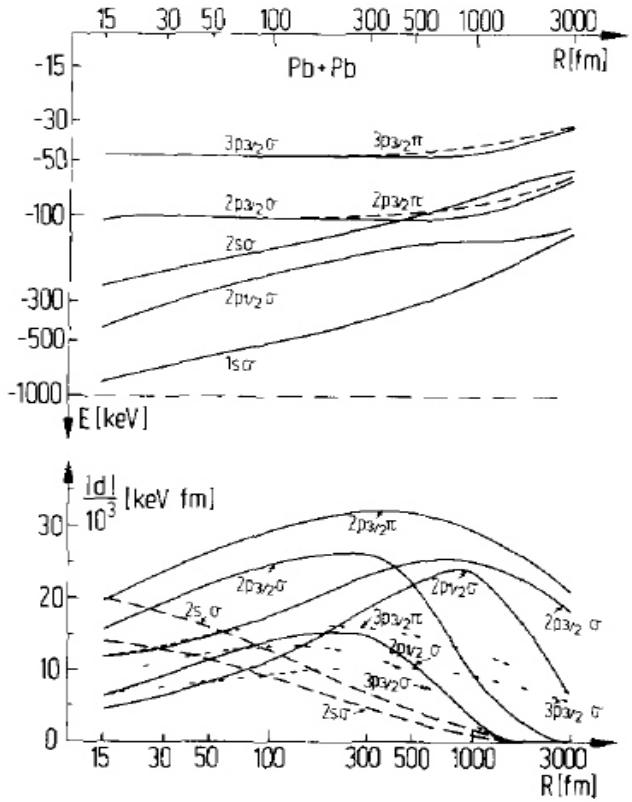
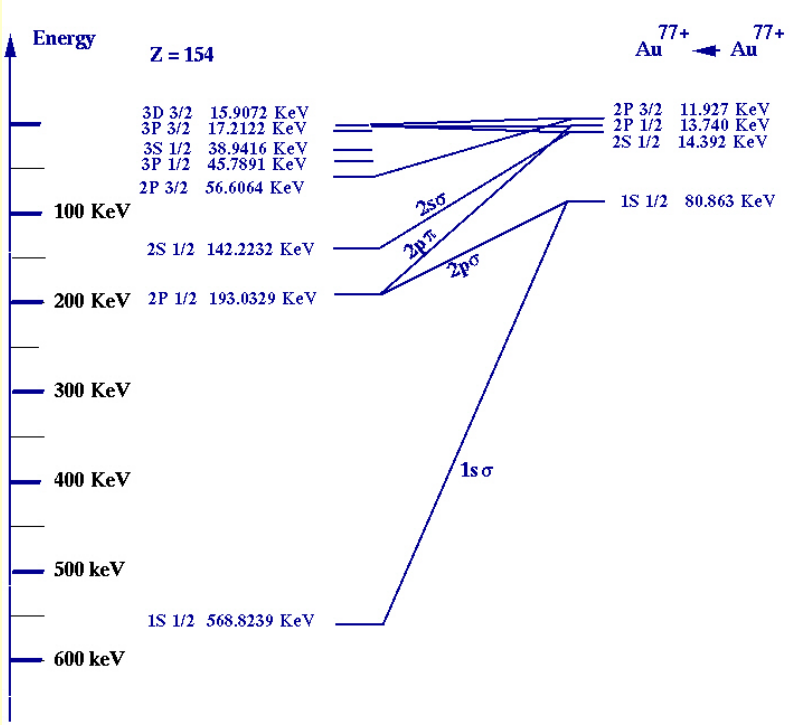


Fig 1 (a) The correlation diagram for Pb–Pb (b) The dipole matrix elements in the long wavelength approximation

My preliminary MO diagram for the Au^{77+} on Au^{77+}

United atoms



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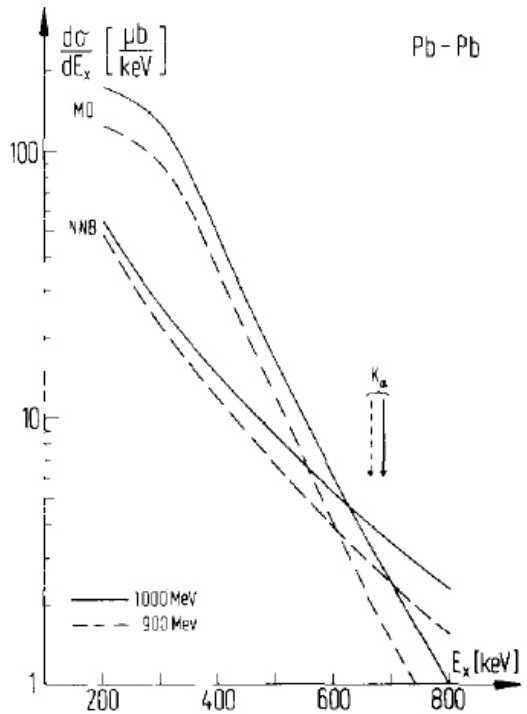


Fig 2 The MO-spectrum and the NNB background at two projectile energies The solid lines correspond to 1000 MeV and the dashed lines to 900 MeV (lab energy) The arrows indicate the K transition energy at closest approach

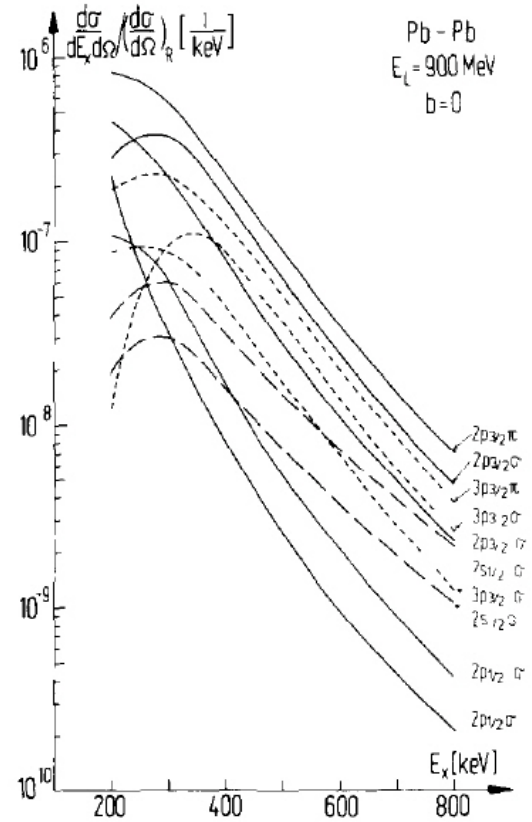


Fig 3 The contributions of the various transitions in dependence of the photon energy at zero impact parameter and 900 MeV bombarding energy

Collisions of the Helium like Gold ions with Al target

Experimental set-up

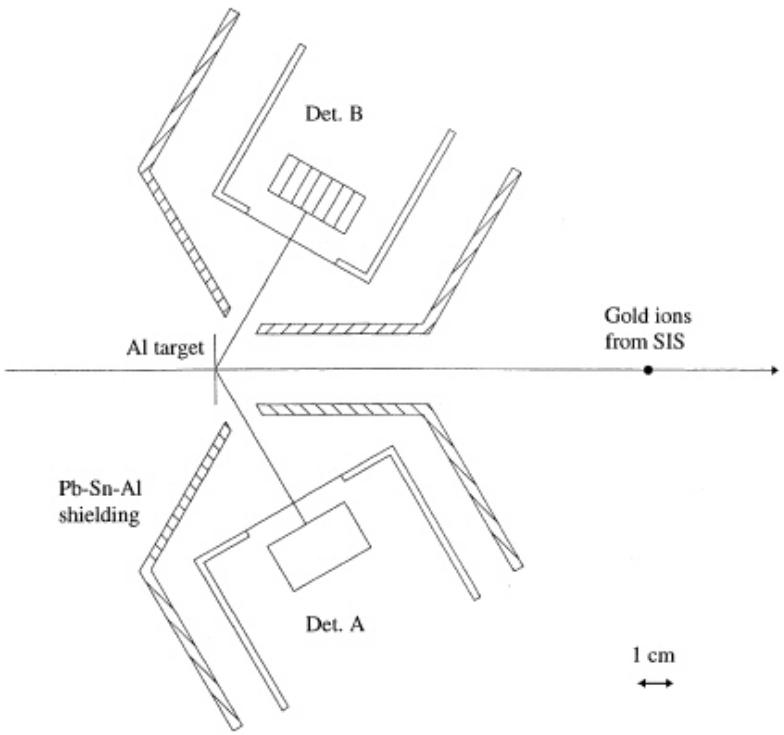


Fig. 2. Experimental setup at the target area.

Two photon decay

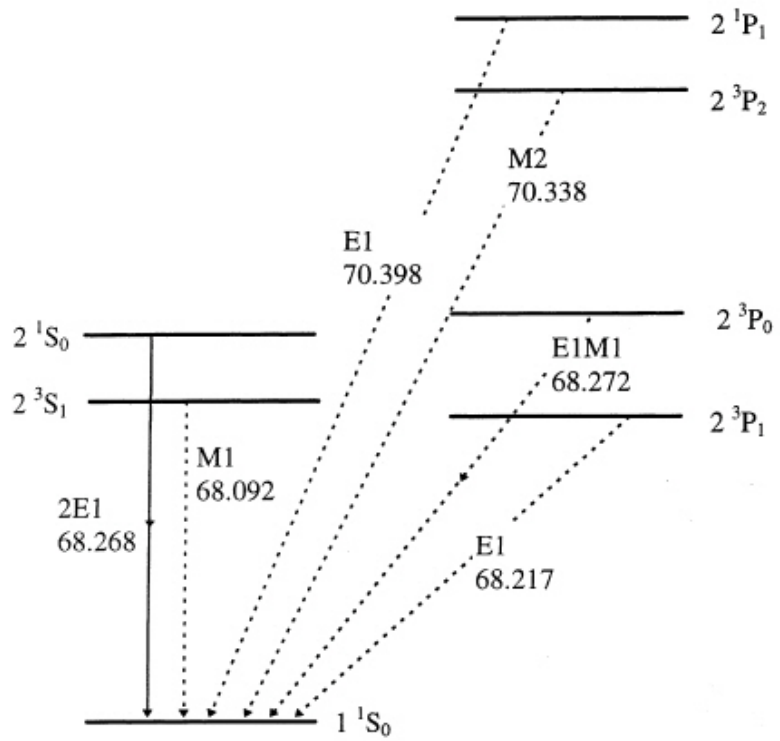


Fig. 1. Level scheme of heliumlike gold including important decay modes. All energies in keV.

- **Details of the experiment proposal and participants**

1. **The first stage: just inject and study Au^{77+} in RHIC**
   - **Measure the emittance by IPM**
   - **Change the RF conditions**
   - **Different intensities**

2. Participants or people who have shown interest:
Leif Ahrens, Waldo MacKay, Woody Glenn, George Parzen, Mike Blaskiewicz, Mike Brennan, Christoph Montag, Mei Bai, Peter Thieberger, Nick Tsoupas, Steven Tepikian, Roger Connolly

- **Future developments:**

If there is any emittance reduction without the beam loss:

-Install the X-ray detectors to catch the electron de-excitation.
-Accelerate Au^{77+}

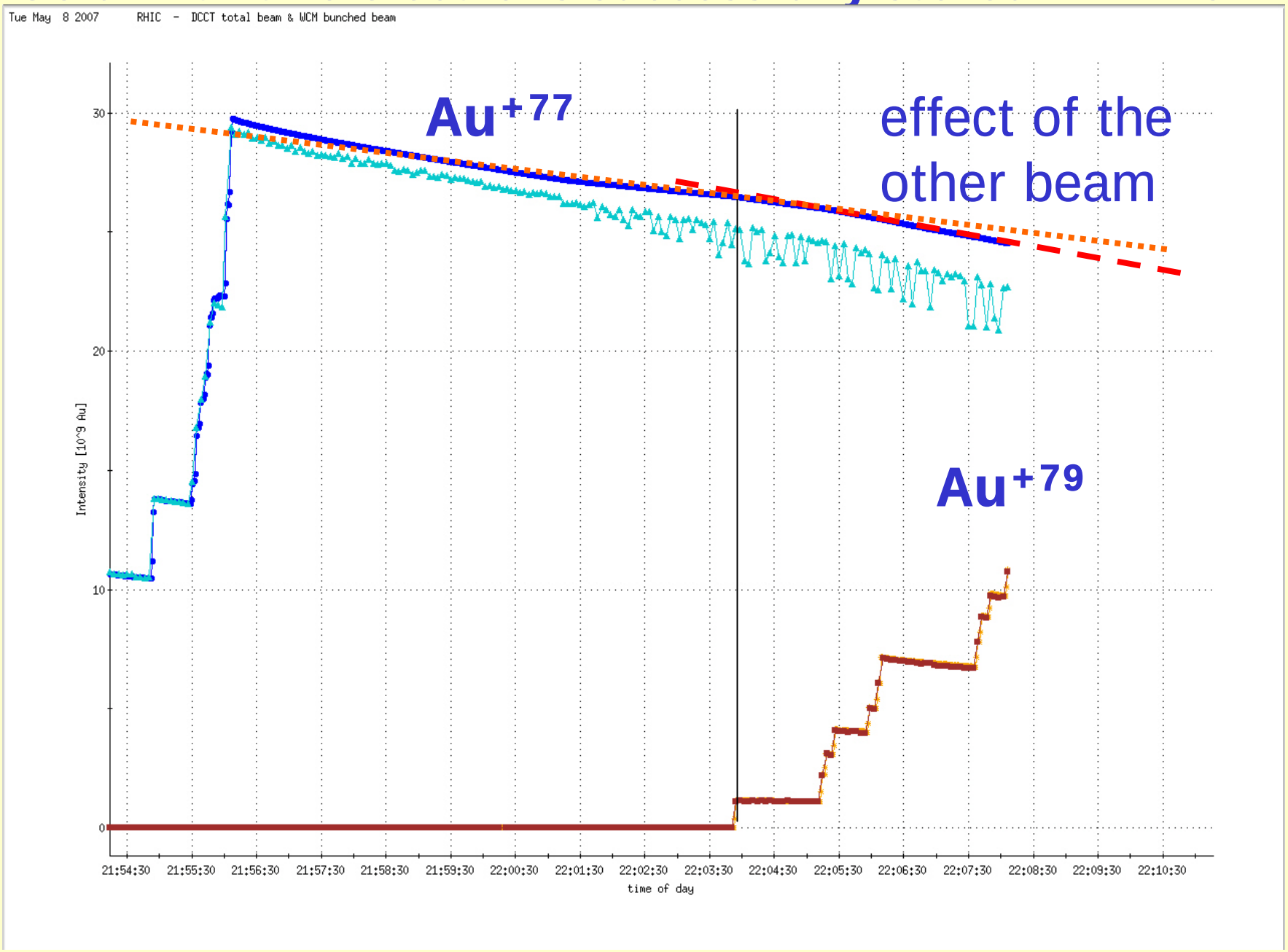
Experiments with Au^{+77} on May 8 and May 23, 2007

Participants:
Leif Ahrens, Waldo MacKay, Nick Tsoupas, Steven Tepikian, Kip Gardner, Kevin Smith, Tom Hayes, Nick Tsoupas

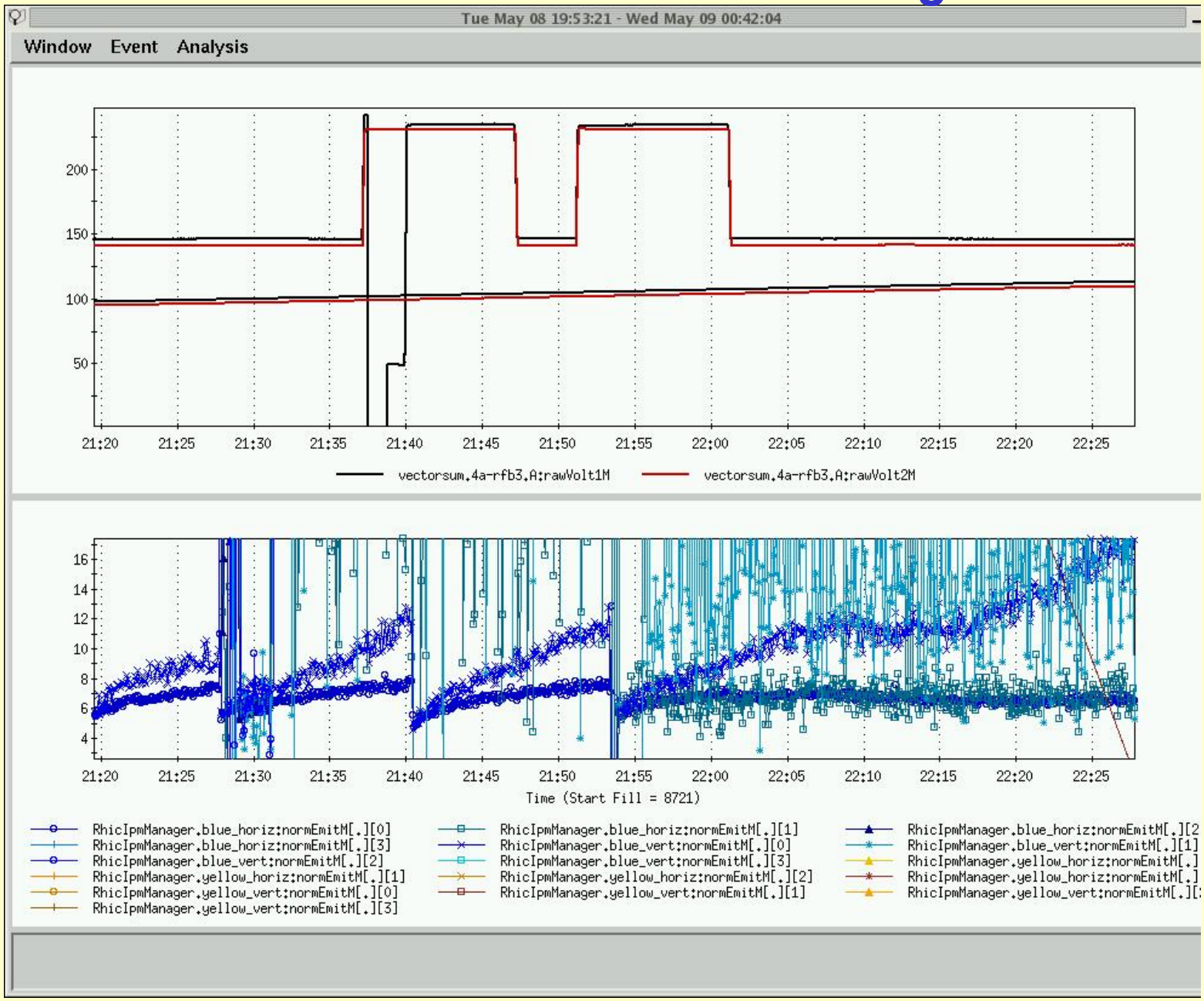
-Leif Ahrens – adjusted parameters in the AGS (magnet field--radius, extraction ..)
- Nick Tsoupas – Adjusted the ATR and extraction
- Steven Tepikian – Worked with the RHIC IPM.
- Kevin Smith, Tom Hayes, Bart Adjusted the RF voltage parameters.
- Waldo MacKay was login the experiments results, vacuum, RF voltages, etc.

This was highly organized and perfectly prepared crew, executing the commands within the minute. The beam Au $^{77+}$ was available in RHIC in 15 minutes!!!

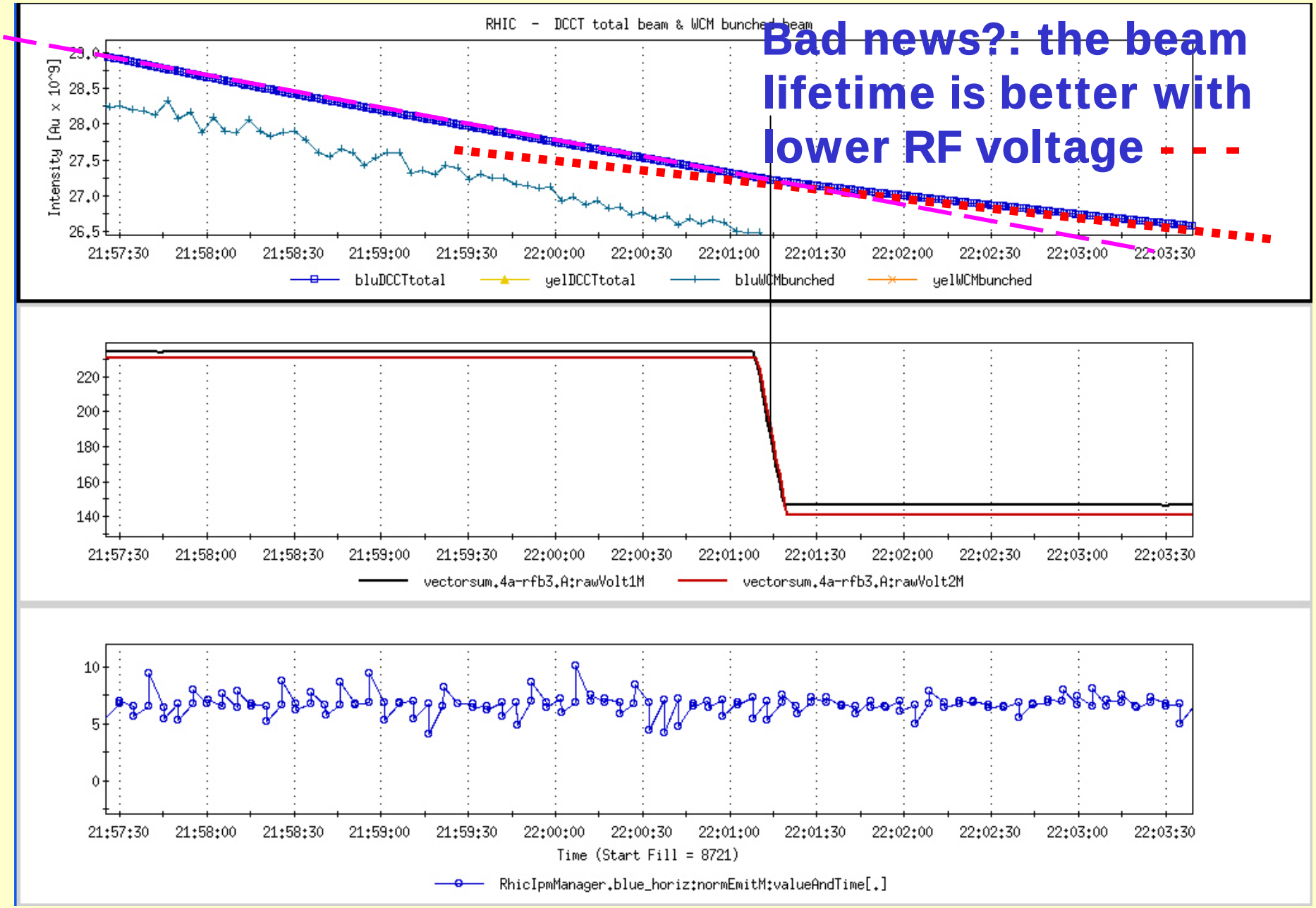
Gold with two electrons successfully stored in RHIC



Emittances vs. RF voltage

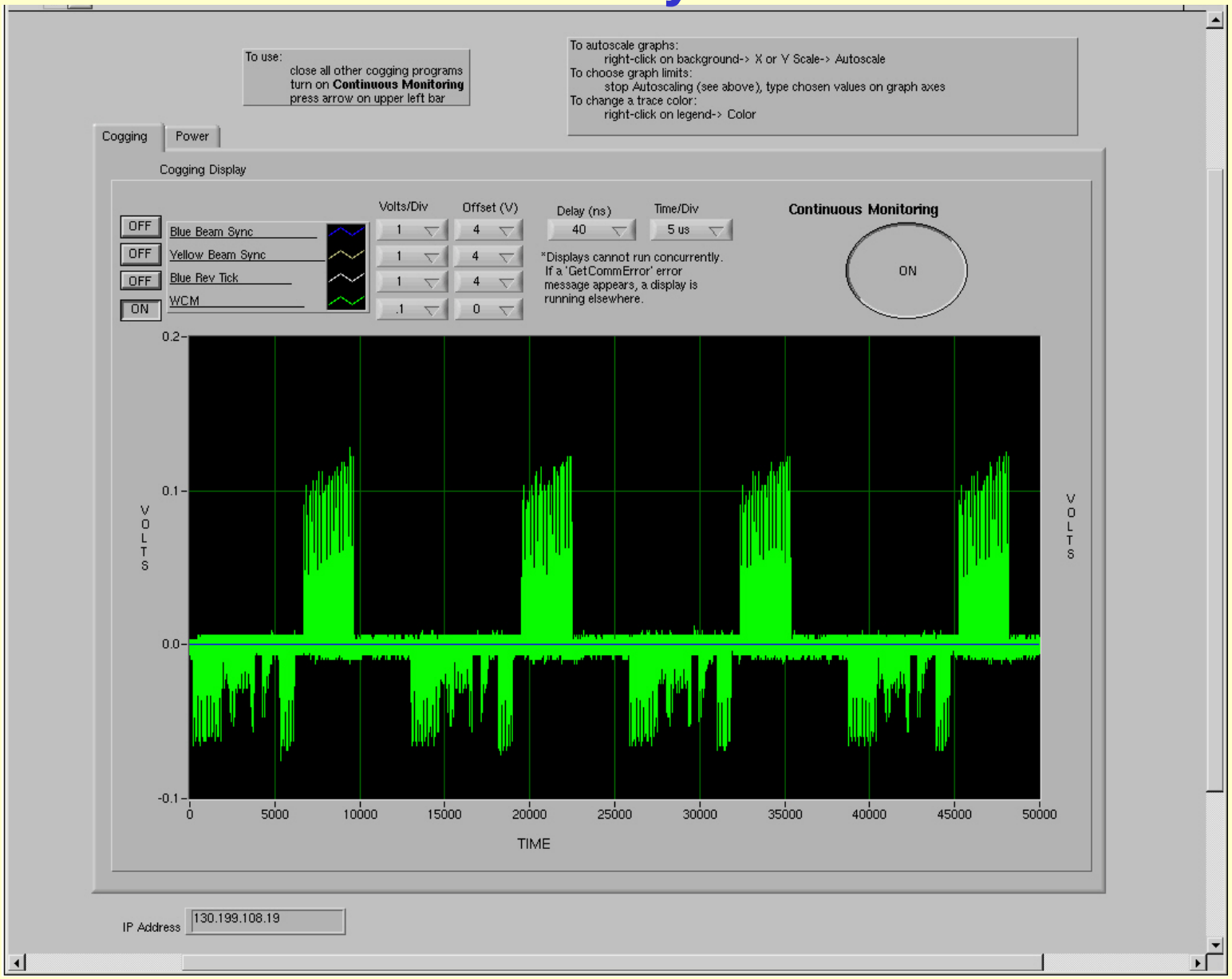


May 8 – the first attempt

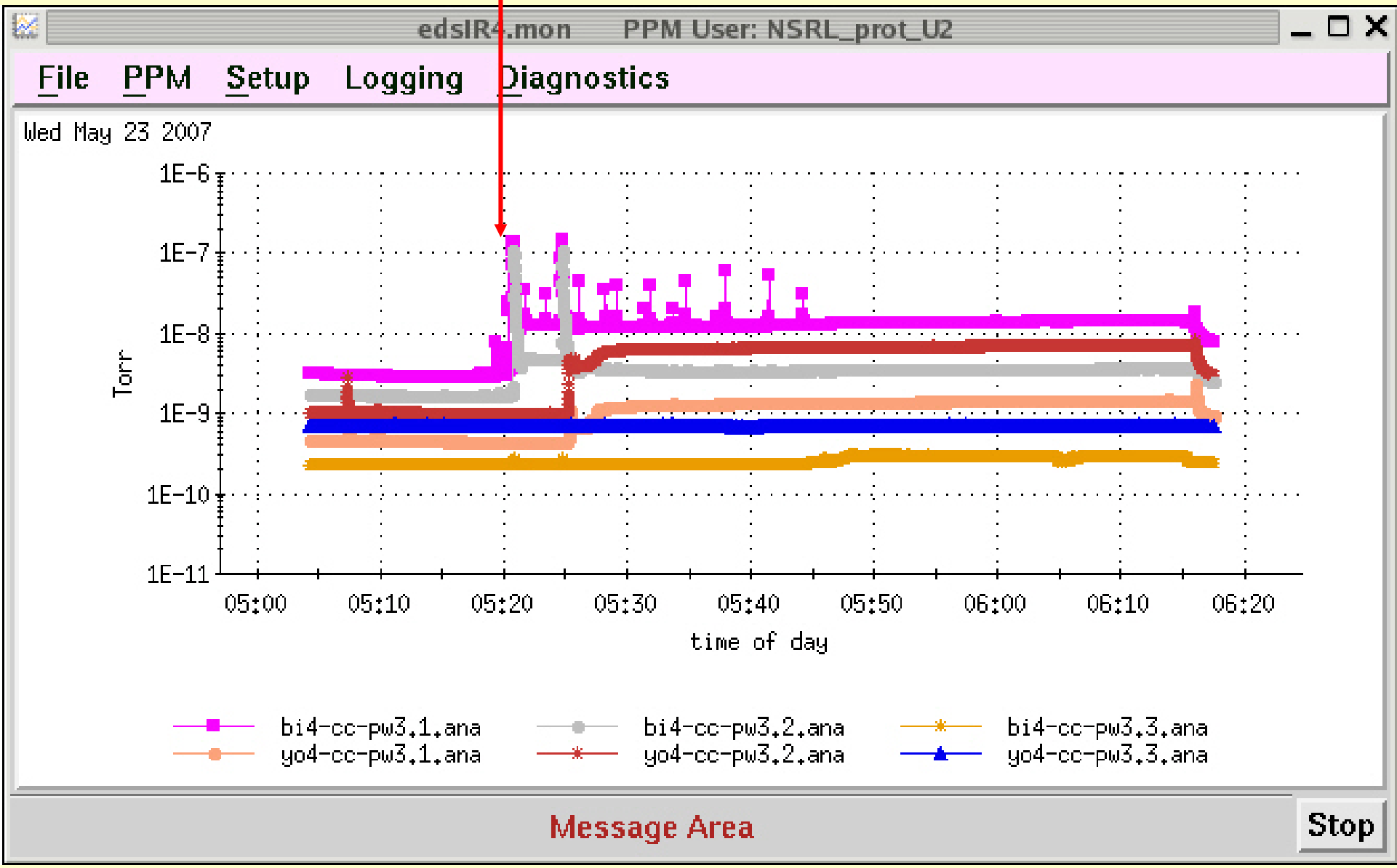


Bad news?: the beam lifetime is better with lower RF voltage

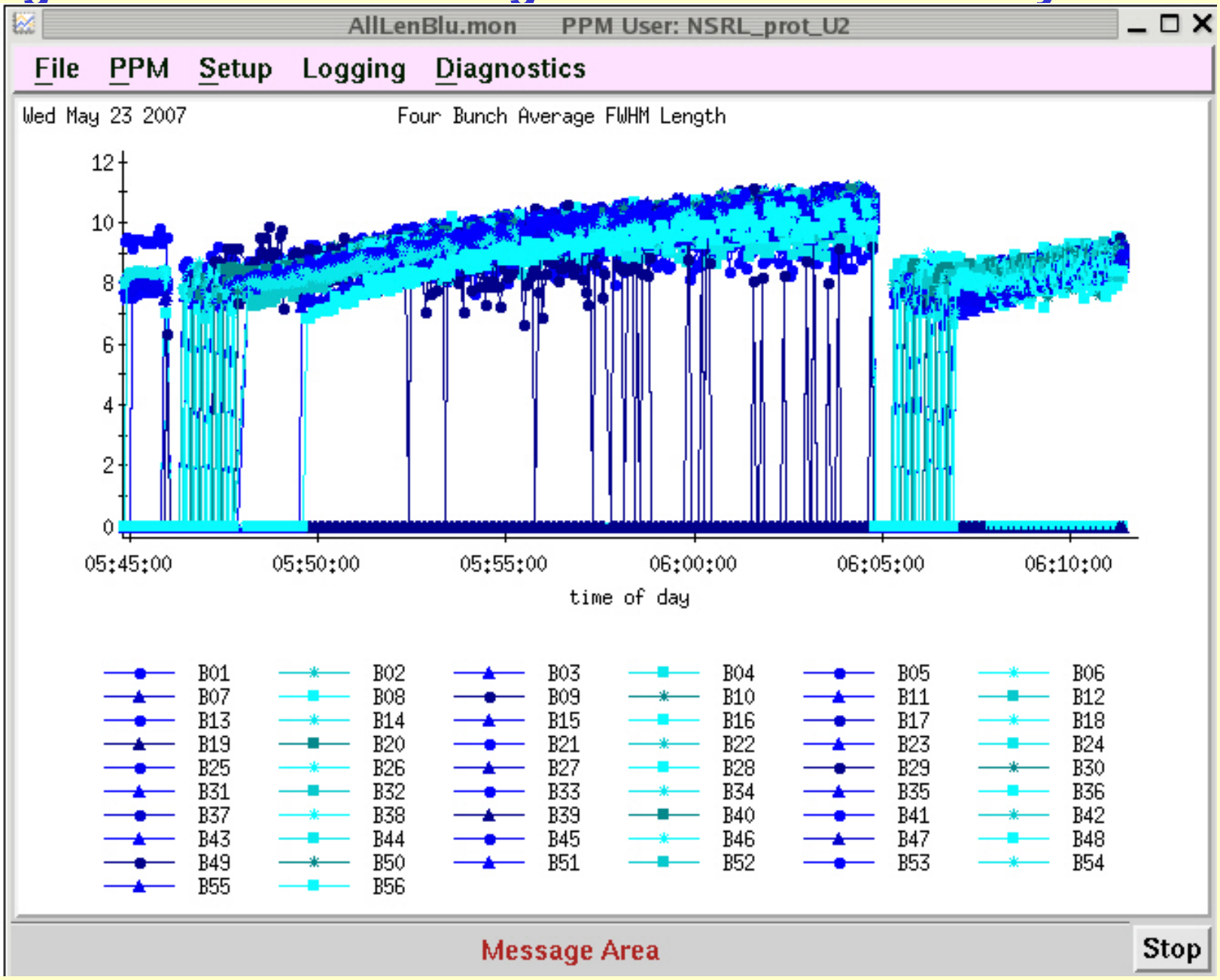
Two beam with different frequencies running at the same time blue Au^{77+} and 'yellow' Au^{79+}



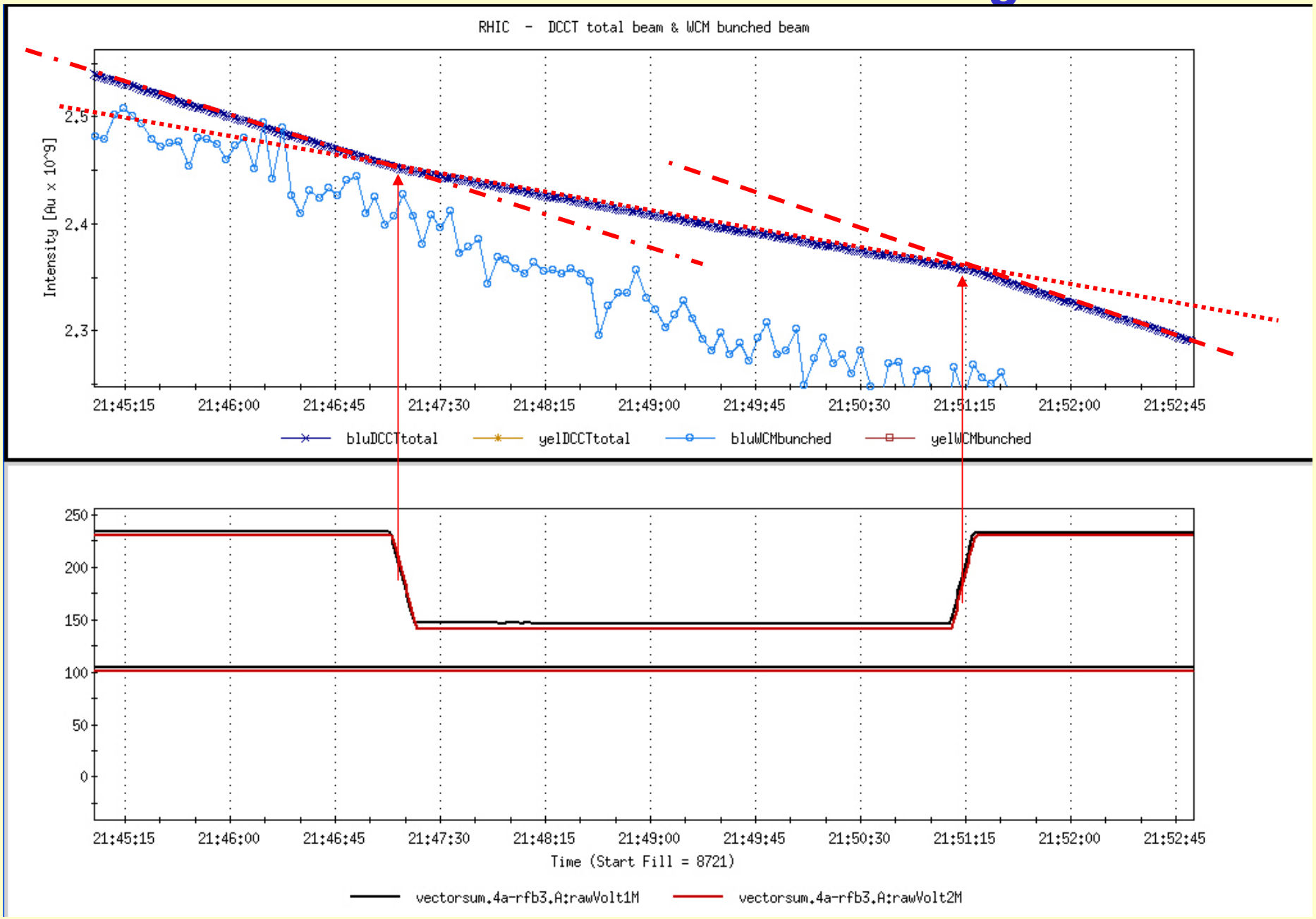
Vacuum pressure after Au^{+77} injection

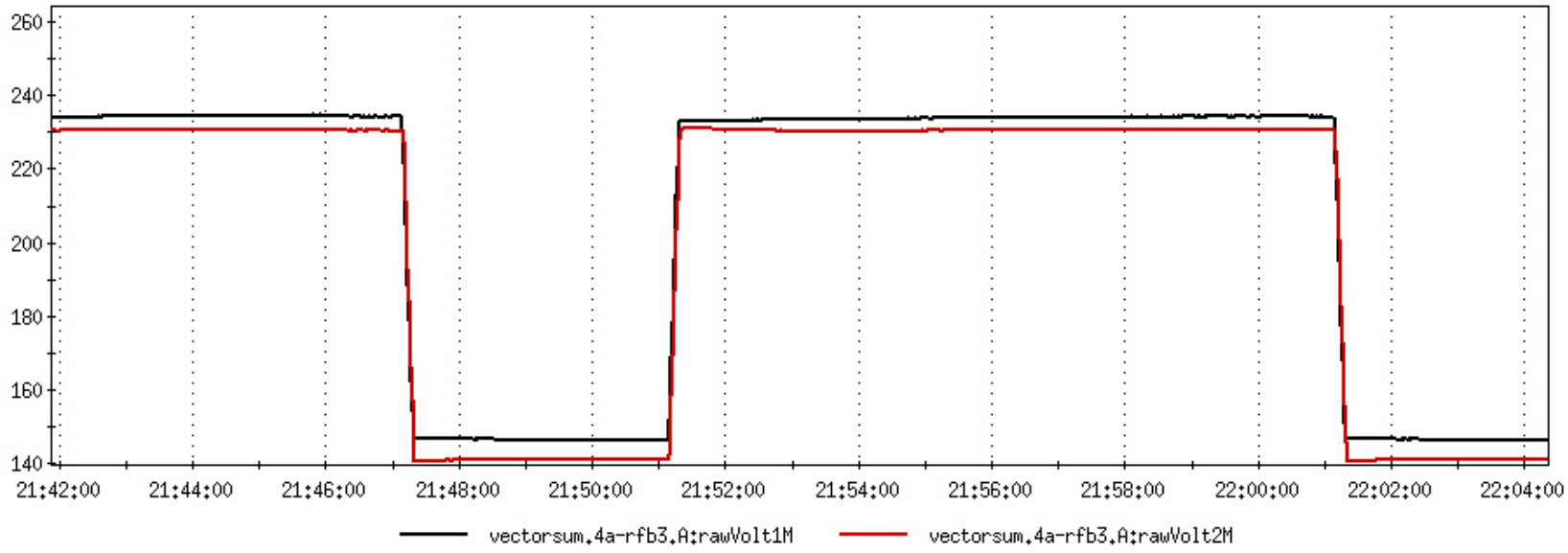


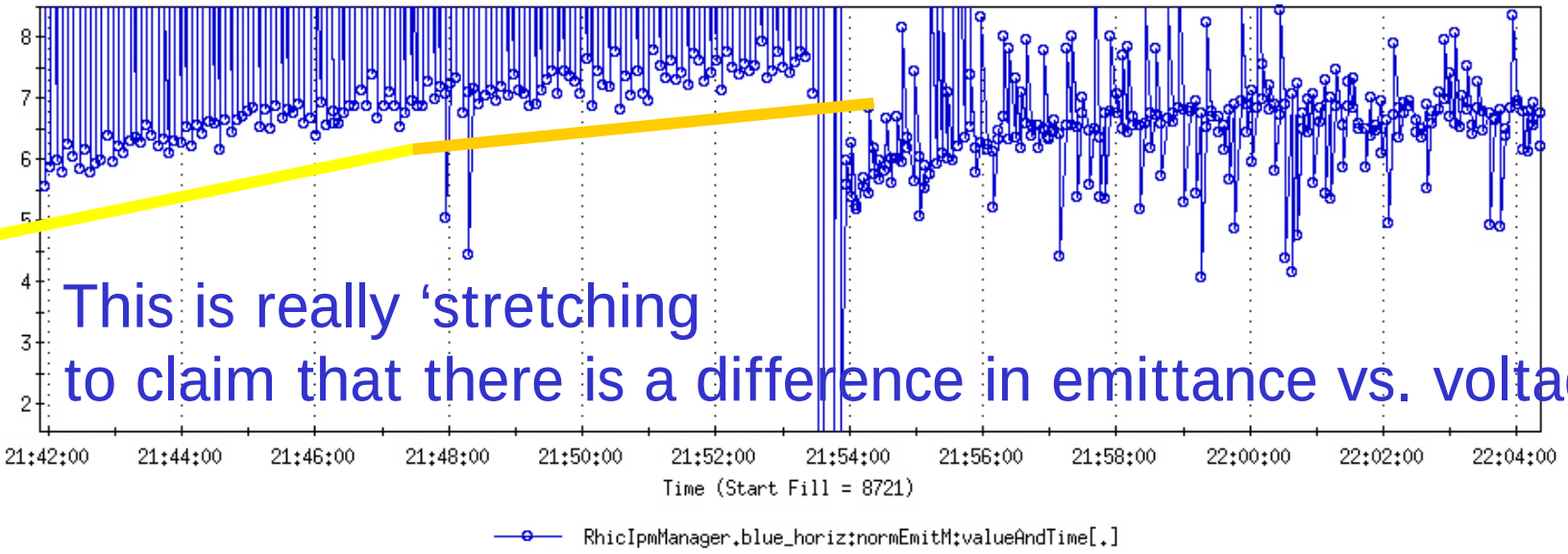
Longitudinal emittance growth Au^{77+} bunch by bunch



Gold ions Au^{+77} vs. RF voltage



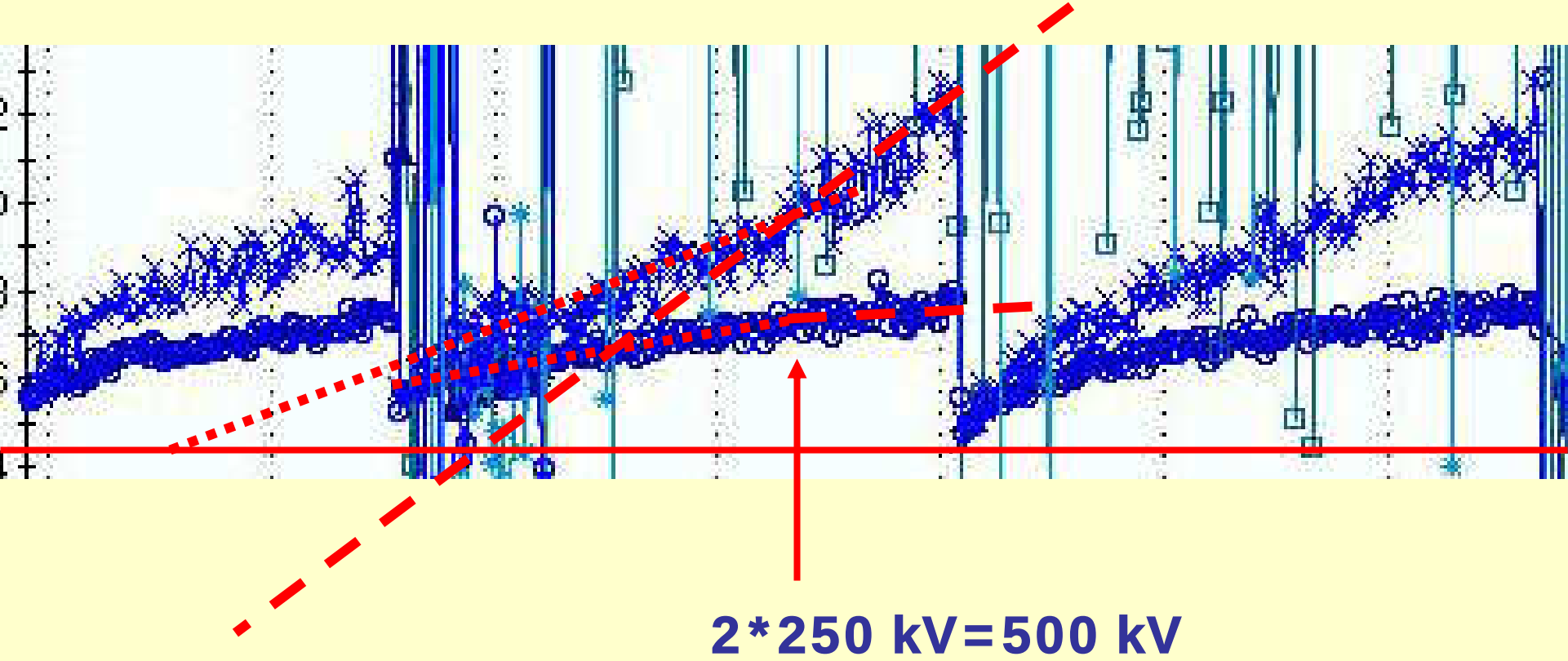




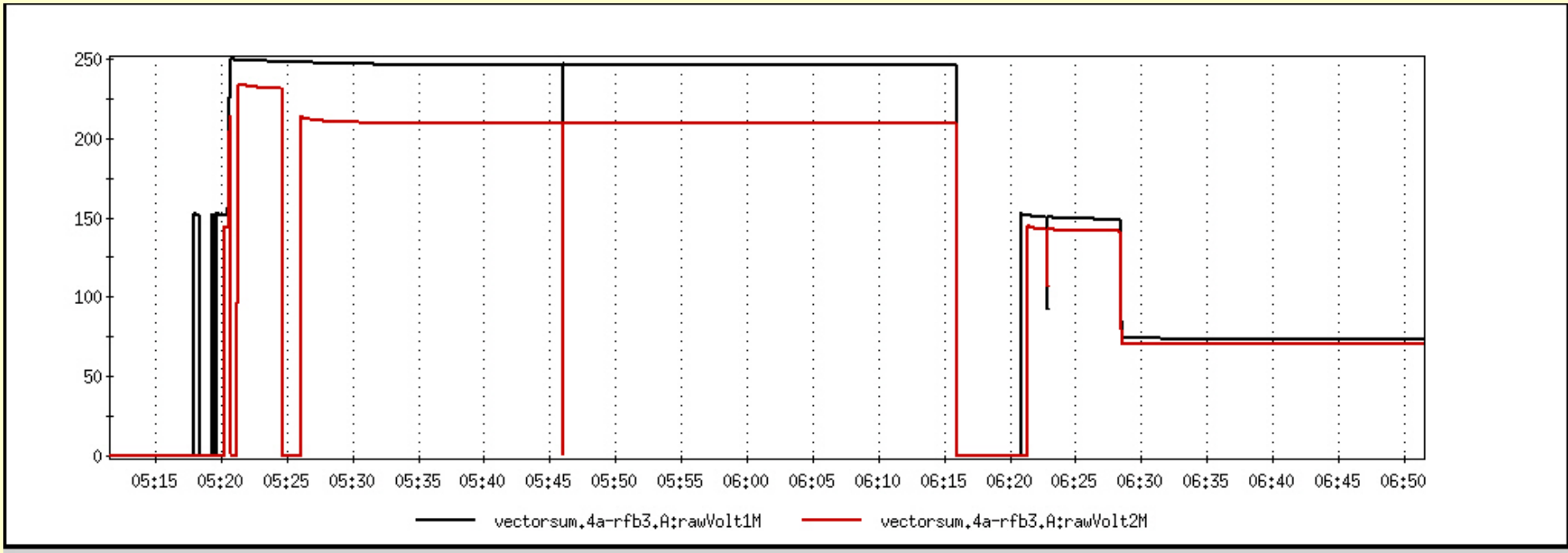
This is really ‘stretching
to claim that there is a difference in emittance vs. voltage

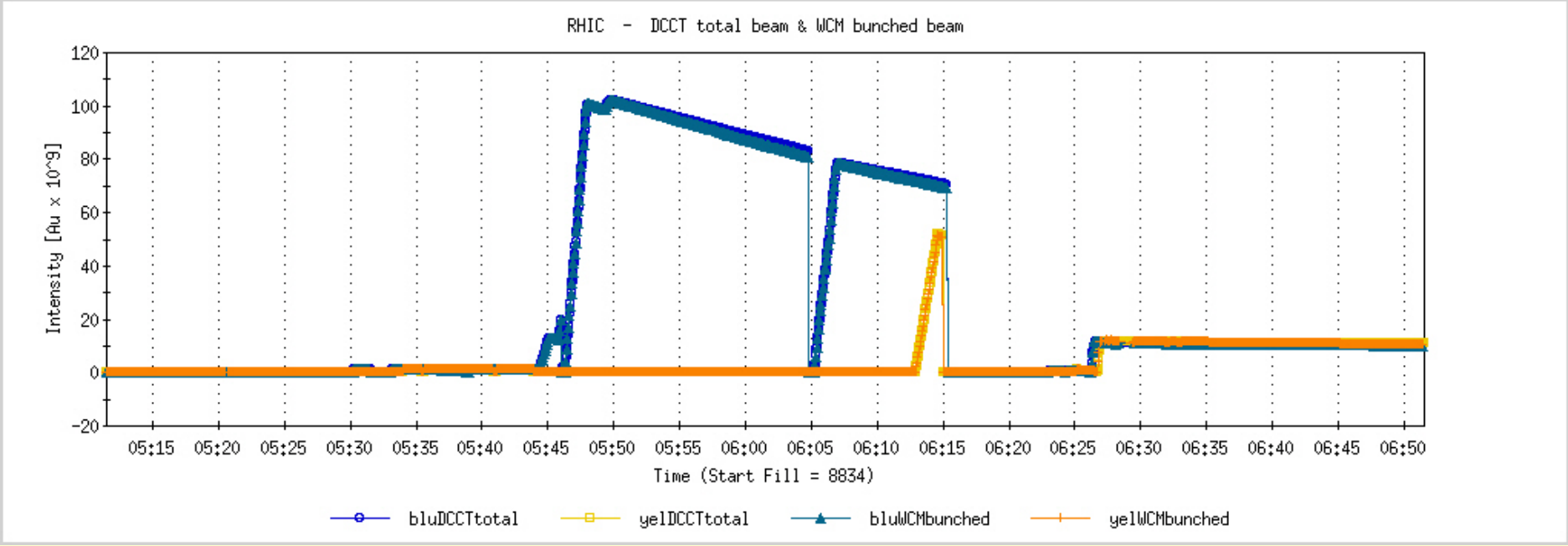
Smaller initial emittance with larger voltage?

With the higher RF voltage – denser bunches - the vertical emittance growth was observed, but smaller growth in the horizontal emittance.

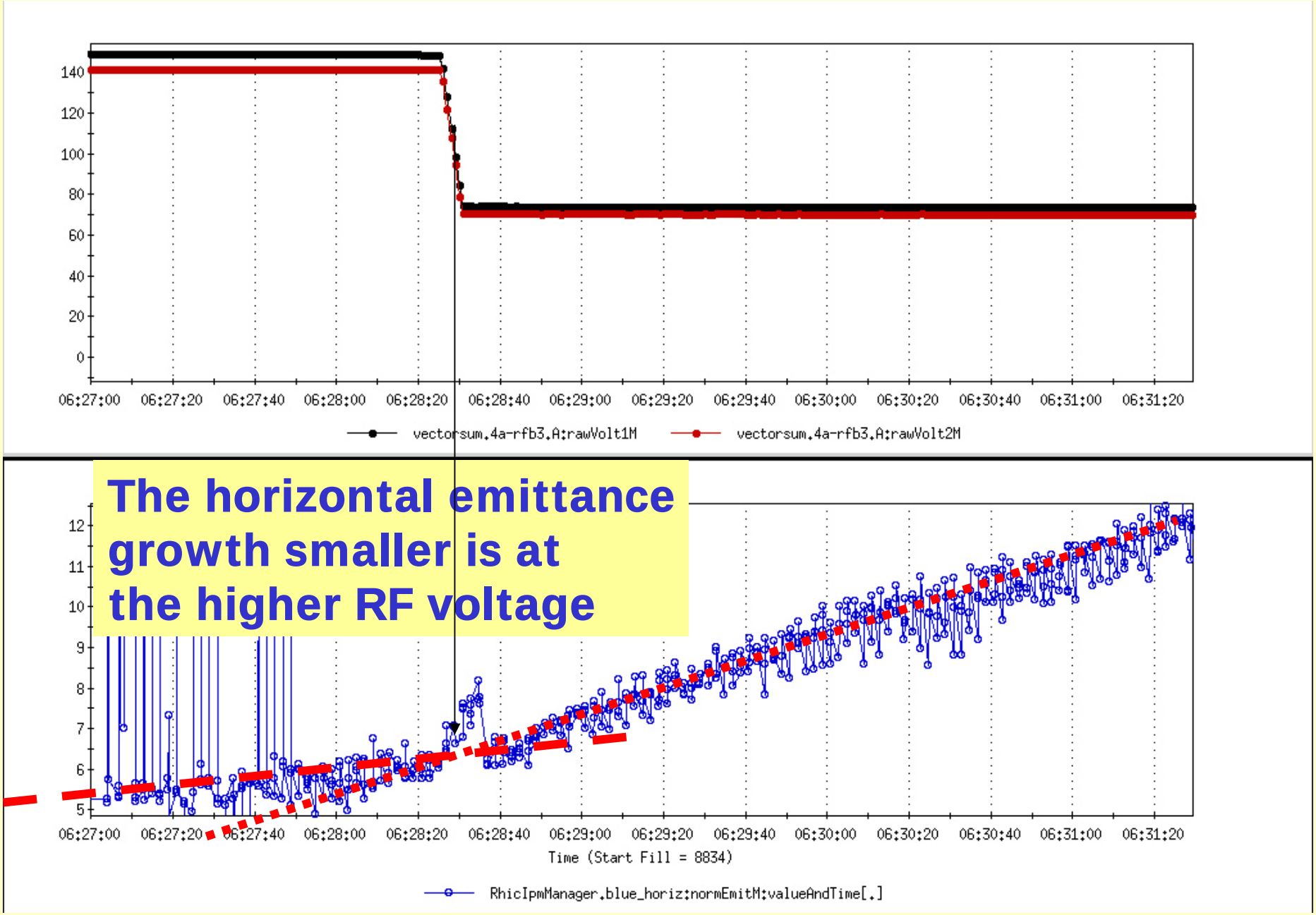


May 23, ion beam current Au^{+77} vs. RF voltage



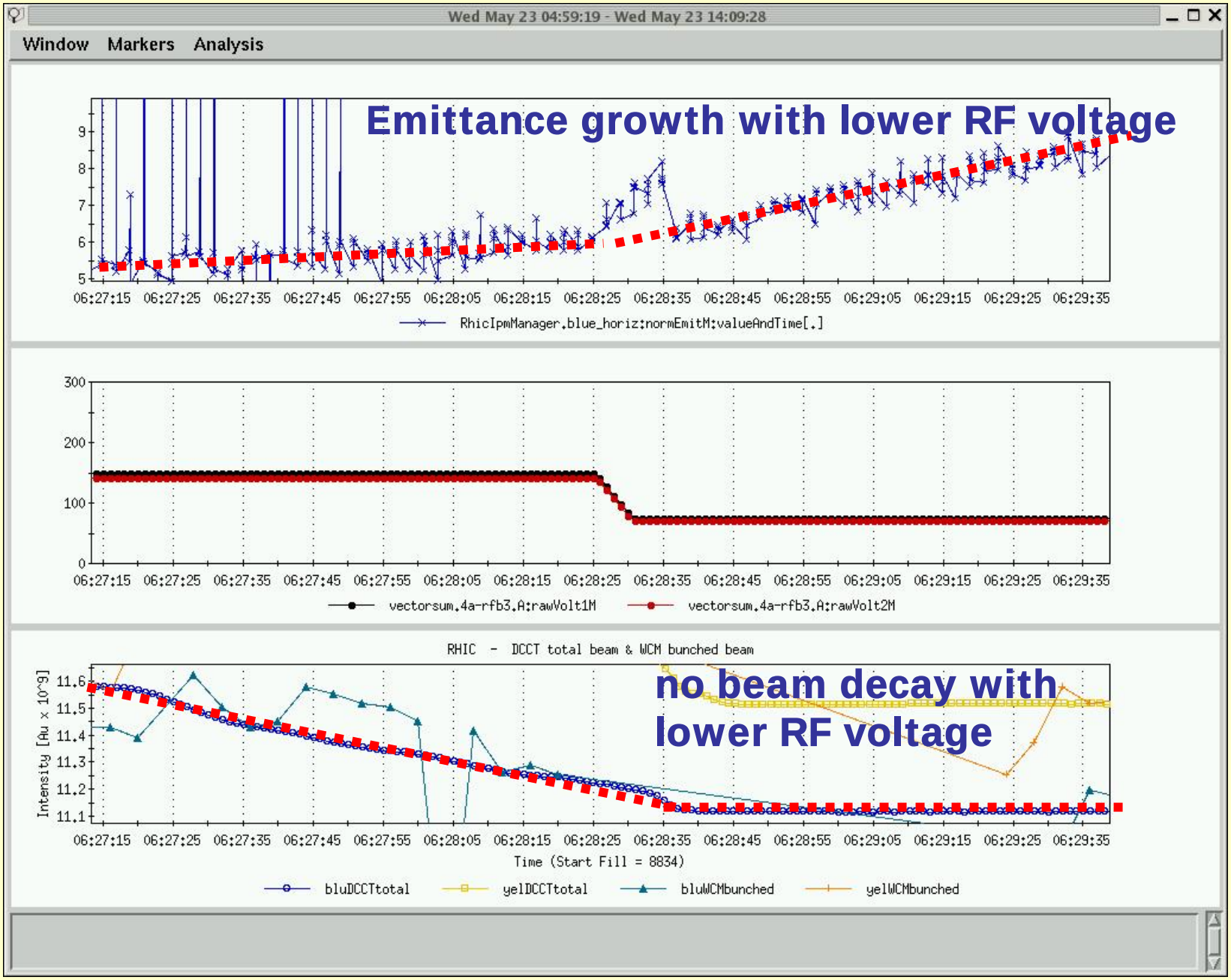


May 23, ion beam current Au^{+77} vs. RF voltage

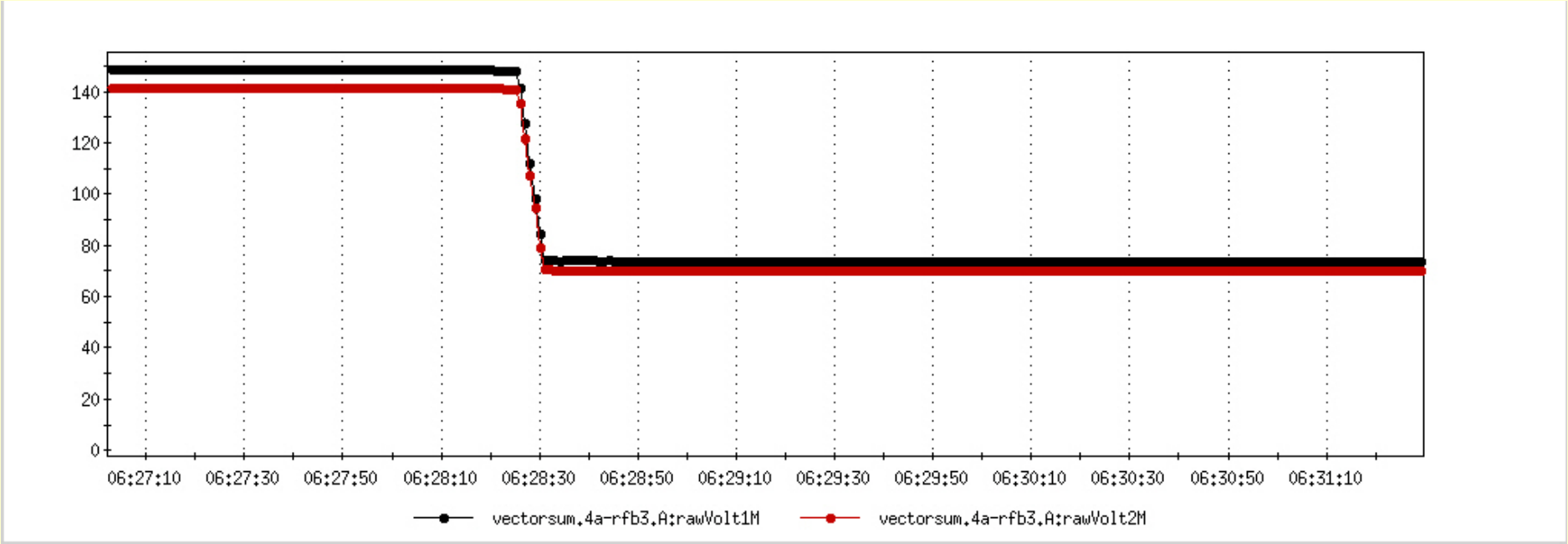


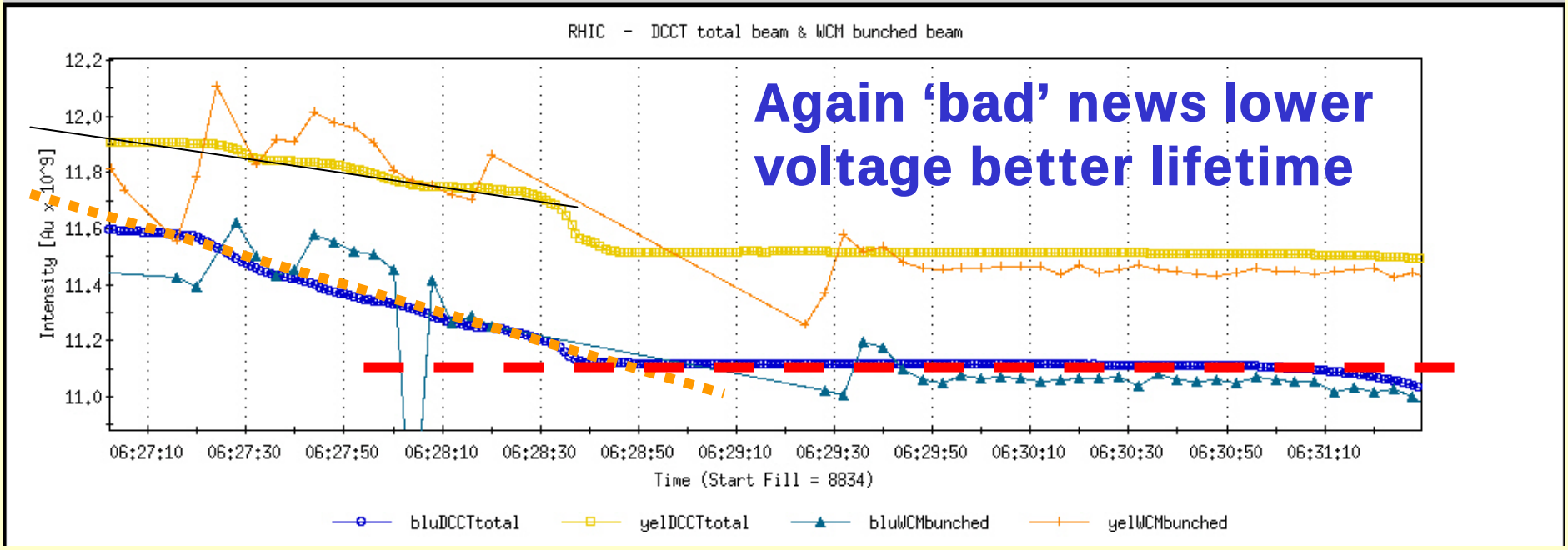
The horizontal emittance growth smaller is at the higher RF voltage

‘Contradictory’ results with and without higher RF voltage



May 23, ion beam current Au^{+77} vs. RF voltage - Details





Again 'bad' news lower voltage better lifetime

Summary from the two experiments:

Two experiments with injecting and storing gold ions with two electrons were very successful.

- We have showed that gold ion beams could be stored at RHIC injection energy without any problem.
- The influence of the RF voltage on the Au^{+77} stored beam:
  - has clearly shown worse beam decay with higher voltage, opposite to the expected 'cooling' effect.
  - it is not absolutely clear if the horizontal emittance growth was smaller with higher RF voltage.
- Ion beam intensity dependence on possible cooling has not yet been studied.
- A possible effect of the beam-gas interaction on cooling has not yet been studied.

We need more studies to see if there is a cooling of the gold ions Au^{+77} with two electrons in the AGS.