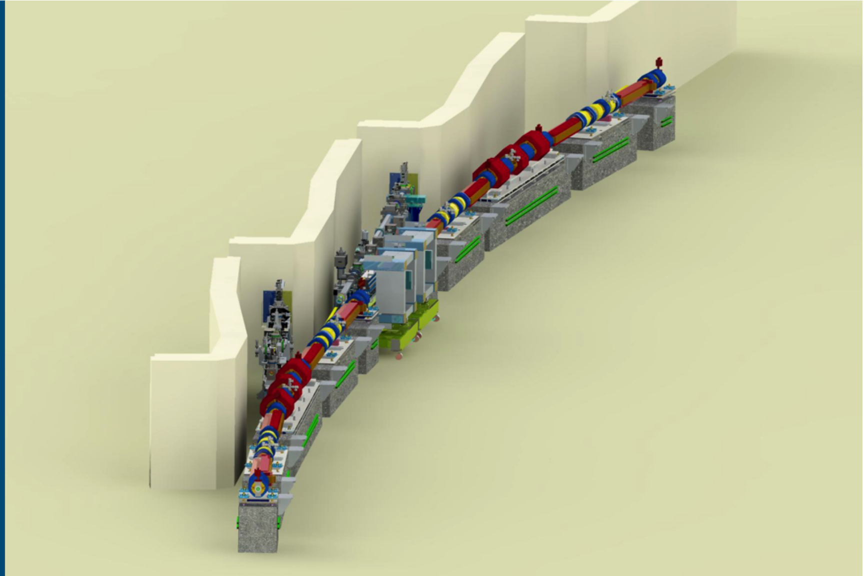
U.S. DEPARTMENT OF ENERGY

Argonne National Laboratory is a U.S. Department of Energy laboratory managed by U Chicago Argonne, LLC.

Argonne NATIONAL LABORATORY

Validation of APS-U Beam Dynamics Using 6-GeV APS Beam



Louis Emery, Ryan Lindberg, Aimin Xiao and Sirisha Kallakuri

Argonne National Laboratory

International Particle Accelerator Conference 2021

May 24th, 2021

Why Make Simulations and Measurements of APS at 6 GeV ?

- APS ring running at 7 GeV is well understood, i.e. simulations and measurements agree, e.g. optics, instabilities, lifetime
- APS Upgrade (APS-U) is also "understood" through extensive tracking simulations and calculations of lifetime and instabilities
- APS-U have extremely low horizontal emittance (41 pm versus 2500 pm) and low α_c (4×10^{-5} vs 2.8×10^{-4}), which is new for us.
- Let us validate the codes for APS-U with a beam that approaches that of APS-U, i.e. APS running at 6 GeV
  - Damping time is similar → Impedance effects may be similar
  - Ion effects is covered by J. Calvey at this conference https://whova.com/portal/webapp/ipaci_202105/Agenda/1678596
- 6 GeV operation has higher rf bucket and allows higher stored current

Calculations and Measurements at 6 GeV

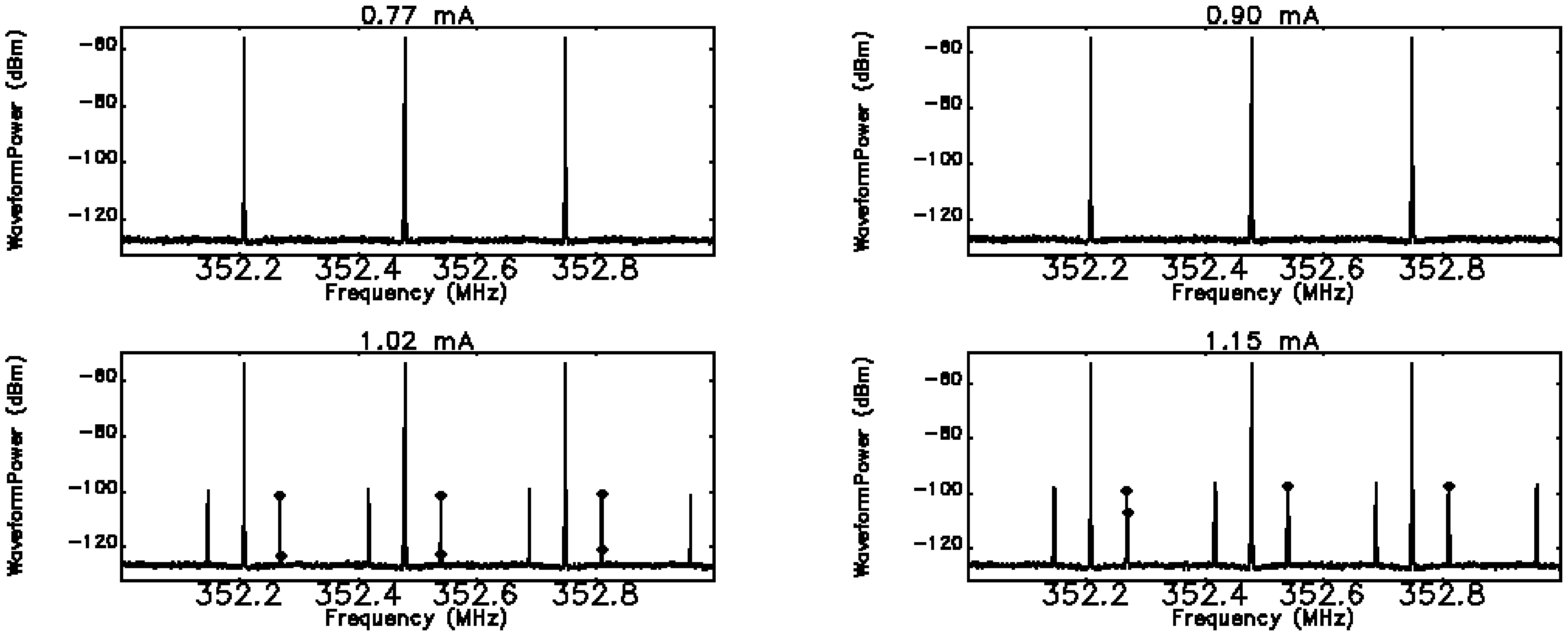
- In a way calculations or simulations are easier than measusements, though may take a lot of CPU time
- Calculation and simulations have known conditions, controlled by user
  - One can set up for a special effect, i.e. resistive wall instability
- Measurements have to be set up carefully to remove all confounding aspects, i.e. avoid instabilities due to other effects or setup minimum coupling, make sure linear optics is corrected
- Of course, simulations can be repeated with the observed experimental errors (e.g. calibrated lattice)
- Ideally, simulation and measurement should be done independently to prevent confirmation bias, or the tendency of one to try to match the other some some tuning of parameters.

Possible Measurements at 6 GeV

- Single bunch instability limit
  - When bunch starts to oscillate in either x or y plane
  - Vary chromaticity (ξ), rf gap voltage (V_{rf}), and feedback system gains
- Multi-bunch instability in x or y planes from resistive wall impedance
  - Detected with spectrum analyzer (SA) on stripline and with emittance growth
  - Vary chromaticity (ξ), rf gap voltage(V_{rf}), and feedback system gains
- Multi-bunch instability in x, y, or z plane from rf cavity dipole or monopole resonator impedance (HOMs)
  - Done with 7 GeV mostly, but 6 GeV could be used as test
  - Use Dimtel box processing and SA on RF cavity HOM probes
  - Started in 2018
  - Feedback available in x and y planes only
- Lifetime comparison with calculation

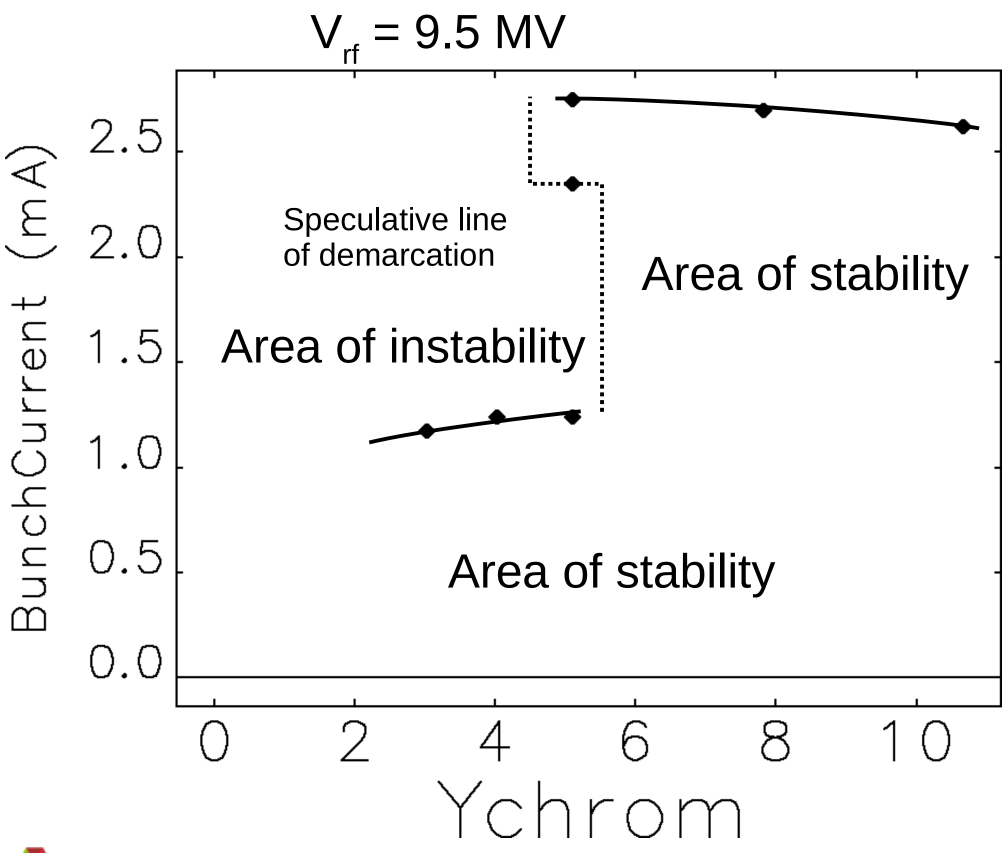
Single bunch threshold

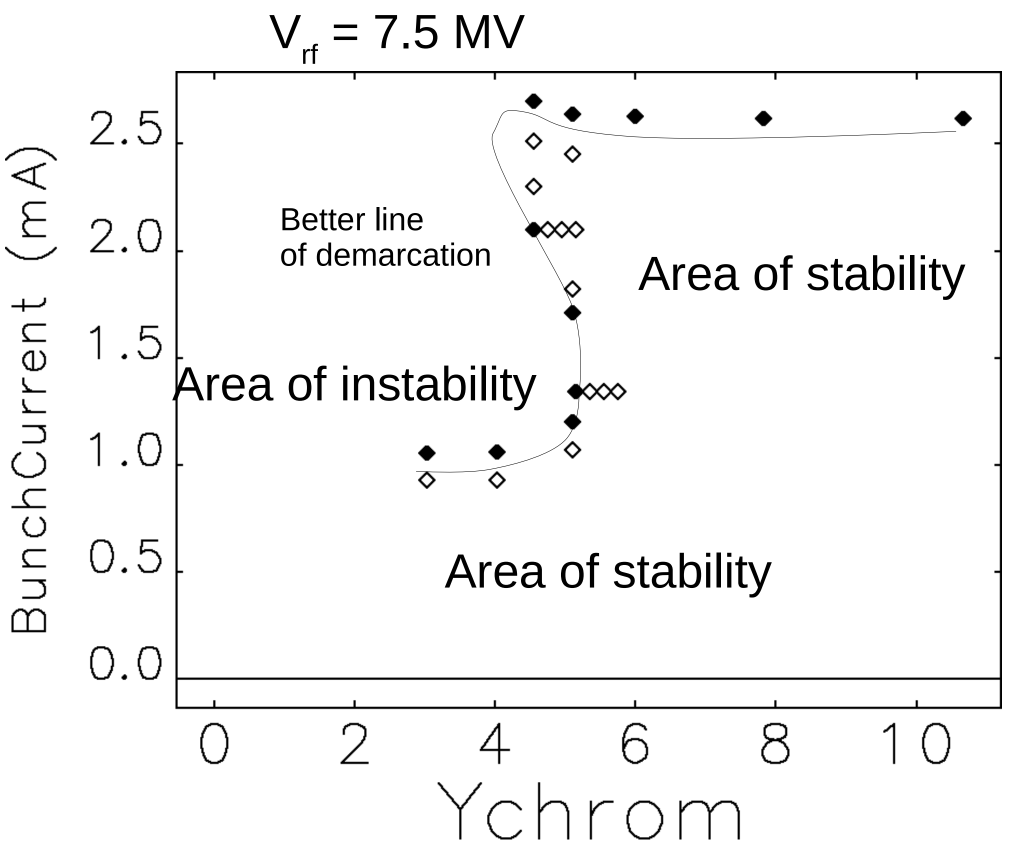
- Use spectrum analyzer to detect x or y motion of single bunch at 6 GeV
  - Not enough photons for measuring beam size
- Threshold for one bunch 0.90 mA for 9.5 MV and chromaticity (3.4,2.4)



Single bunch stability peninsula

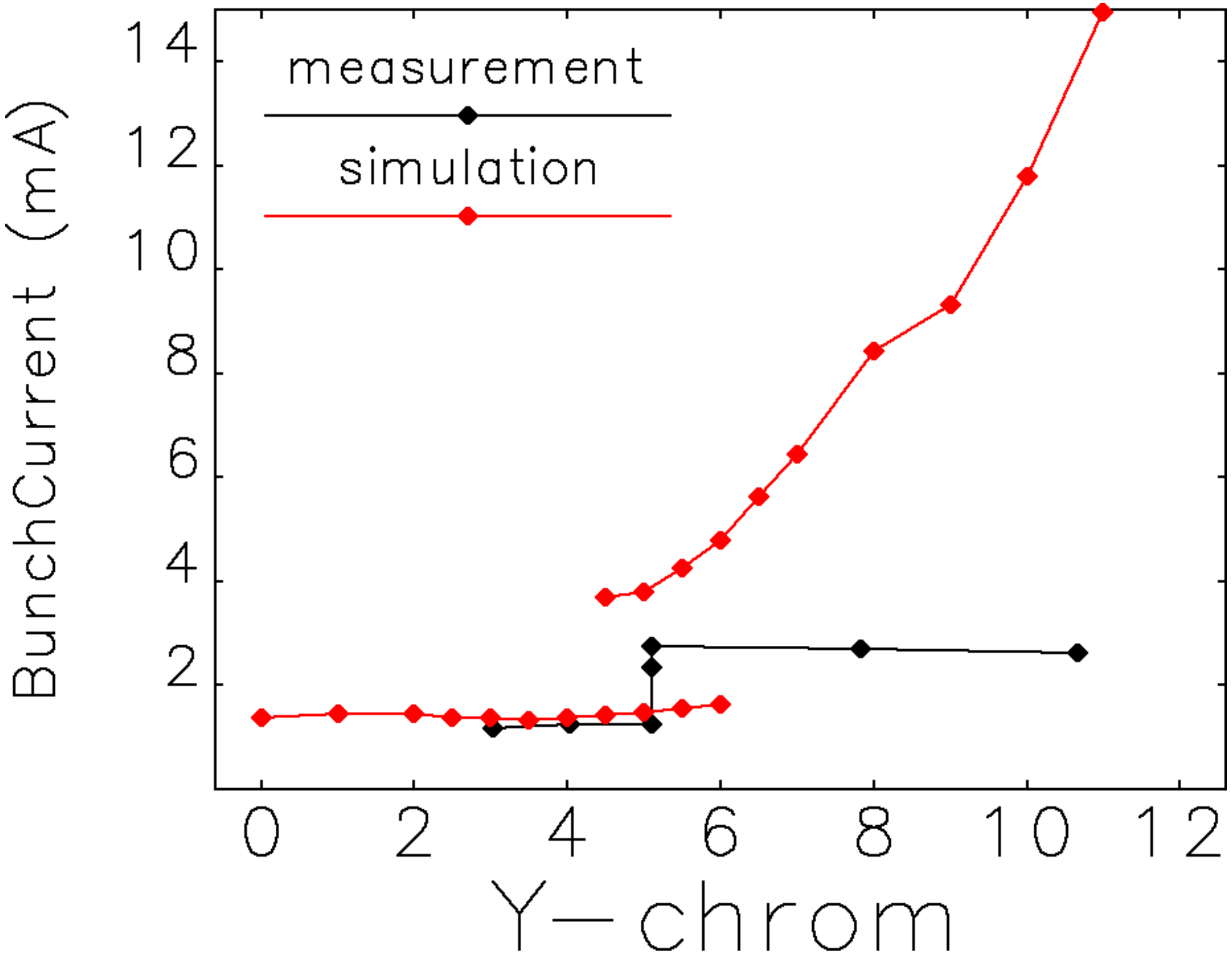
- Found peninsula of stability in first measurement with V_{rf} = 9.5 MV (nominal value)
- Variation with rf voltage is small





Single bunch threshold comparison

- Simulations and measurements at NSLS-II previously indicated a peninsula of stability
- In simulation injecting 3 mA at y-chrom of 5 would give a stable beam, i.e. by not crossing the lower demarcation line by injecting a little bit as a time
- Difference for higher 2nd threshold may be due to difference in x-chromaticity. Simulation used 12, measurement used 5.
  - Try again soon with right ξ_x



Bunch-by-bunch feedback testing

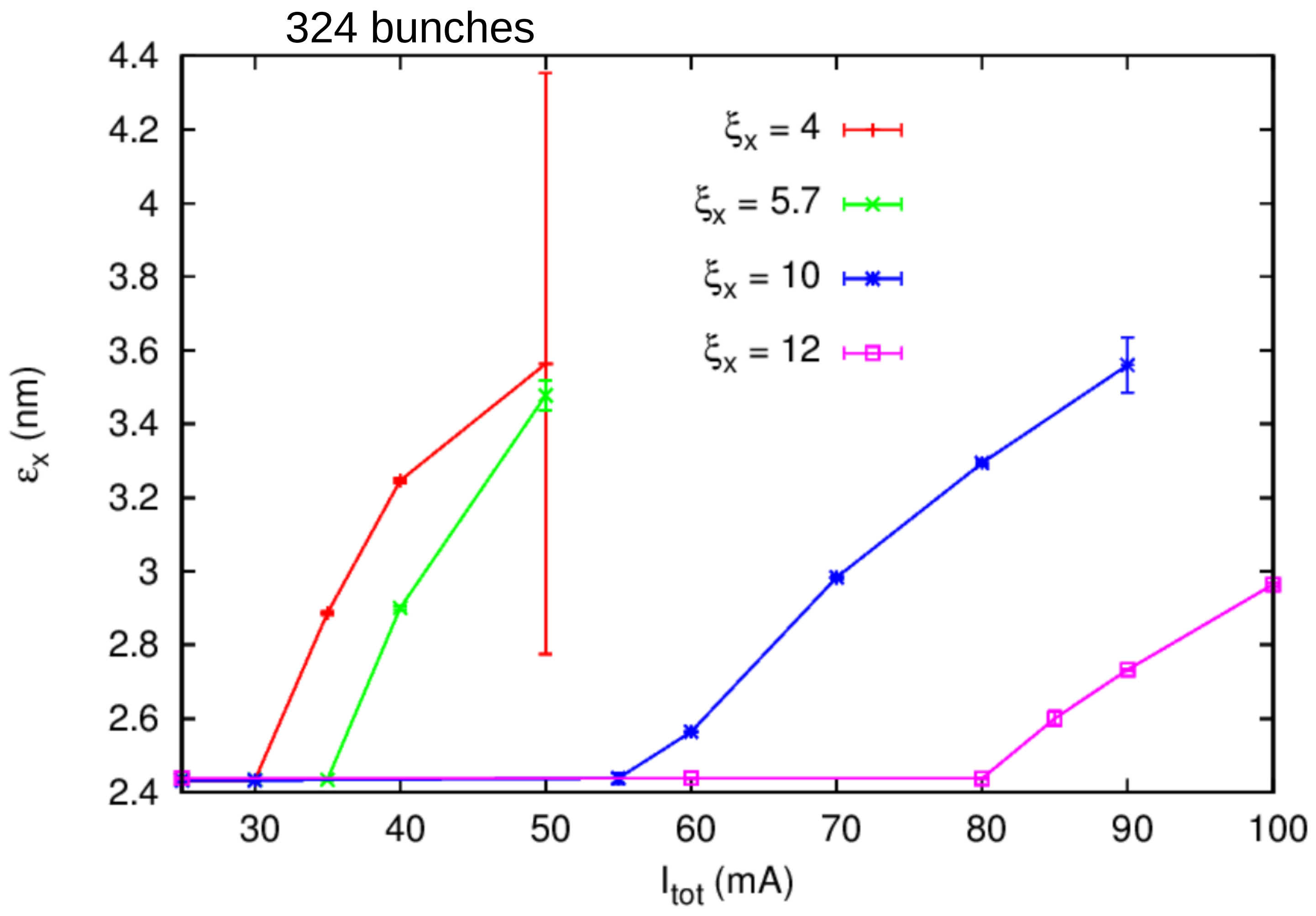
- APS-U purchased two iPg12-1296F Dimtel signal processing boxes along with bpm front ends provided by Dimtel
- Incorporated into our APS 7 GeV operations x and y planes for acceptance testing
  - Can borrow one for longitudinal modes (monopole HOM characterization)
- We are presently characterizing their operation for our studies at 6 GeV
- Drive-damp measurements are a good opportunity for checking feedback in tracking simulations.

Multi-bunch Threshold from Resistive Wall Impedance

- Theory and simulation predict that APS-U beam will be stable from resistive wall impedance because of chromatic damping
- Measurement show that APS at 7 GeV is be stable as well for reasonable ξ_x
- However APS at 6 GeV will not be stable for 324 bunches!
  - Damping is less by $(6/7)^3$
  - Effect of RW impedance is increased by 7/6
  - Landau damping from tune spread is lessened
  - Bunch lengthening from Z_{long} times ξ_x is lessened
  - 24 bunches is stable because of bunch lengthening
- Feedback is not included, but once the threshold current is exceeded feedback cannot reduce the emittance back to that below threshold (because of noise injection)

Multi-bunch Threshold Simulation for RW

- Calculation for ξ_x = 5.7 gives a limit of 35 mA, say, for 324 bunches
- Consistent with a measurement of stability threshold between 37 mA and 100 mA, chrom (5.6,4.9)
- Need to cover more cases



Measurement of Multi-bunch Threshold for RW

- Our measurements were wide-band SA and emittance measurement.
- Individual bunch current must be at least lower than 0.9 mA, i.e. to avoid single bunch instability :(
- Because of ions bunch pattern must include sufficient gaps to selectively detect the RW instability and not the “ions”
- Stable configuration at 324 bunches: 2 gaps of 24 slots (to avoid ions), 0.5 nC/bunch, 37 mA total, chrom (5.6,4.9). Unstable at 100 mA.
- Need to collect more data to show dependence on ξ
- Above threshold emittance was seen to depend transverse feedback gains

Monopole HOM of RF cavities

- Search of HOMs reported in NAPAC 2019, 670 (2019)
  - Found 5 HOM per cavity (60 HOMs) that would have an effect for APS-U
- Impedances characterized at 7 GeV and 6 GeV give equivalent results.
  - Instability at 6 GeV is strong, though
- We have a temperature model of HOM frequencies
  - Function of cooling water temperature and power dissipated in cavity (i.e. rf gap voltage)
  - Reproducible over long term
  - Same for 6 or 7 GeV
- Now need to develop a automated procedure using cooling water temperature that circumvent the resonances and instability when characterizing high current beams for 6 GeV APS
- For example, needed for rf gap voltage scans and rf bucket height scan

Dipole HOM of RF cavities

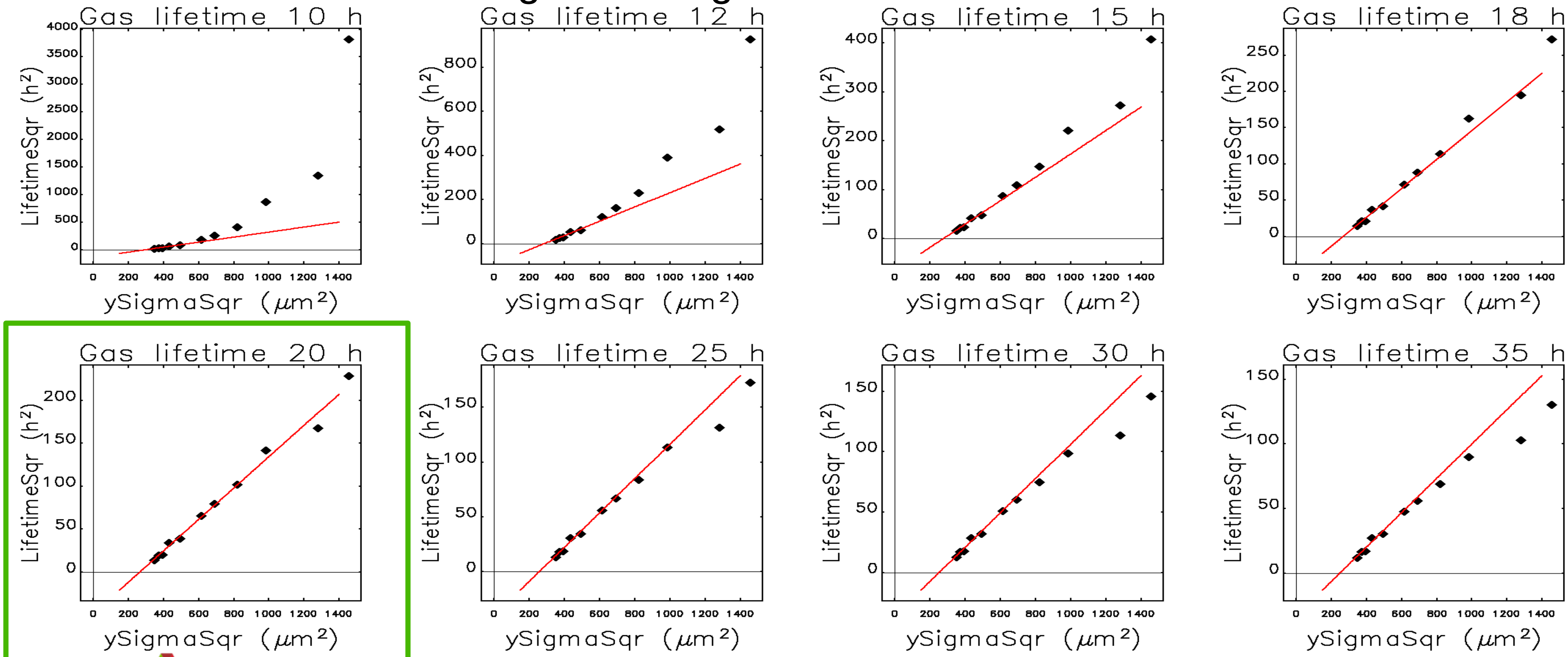
- Initially didn't think they would be important, as coherent damping is expected to be high
- Apparent effect at higher currents (~ 150 mA, 48 bunches) at APS 6 GeV
- Searched for dipole HOMs at 6 GeV at I < 100 mA with Dimtel system for characterization
  - Found only one measurable dipole HOM in one cavity so far. Puzzling.

Lifetime bench-marking requires requires accurate pinhole image resolution

- For the smallest beam the lifetime will be short, and thus we need to measure the vertical beam size σ_y as accurately as possible, near the resolution of system σ_{res}
- Requirement for Touschek lifetime benchmarking (Done for 7 GeV in NAPAC 2016, 940).
- Resolution has been measured previously at 7 GeV to be 18 um (β_y = 24.3 m). However with 6 GeV beam we can reach measured beam size of less than 18 um!! Therefore the resolution is estimated too high.
- Start with minimum coupling, and then scan skew quadrupole knob to generate a vertical dispersion. Use expected linear dependence of $(\text{lifetime})^2$ versus $(\text{measured } \sigma_y)^2$ to get resolution
- Used “bad” sextupoles to give high decay rate for shorter measurement

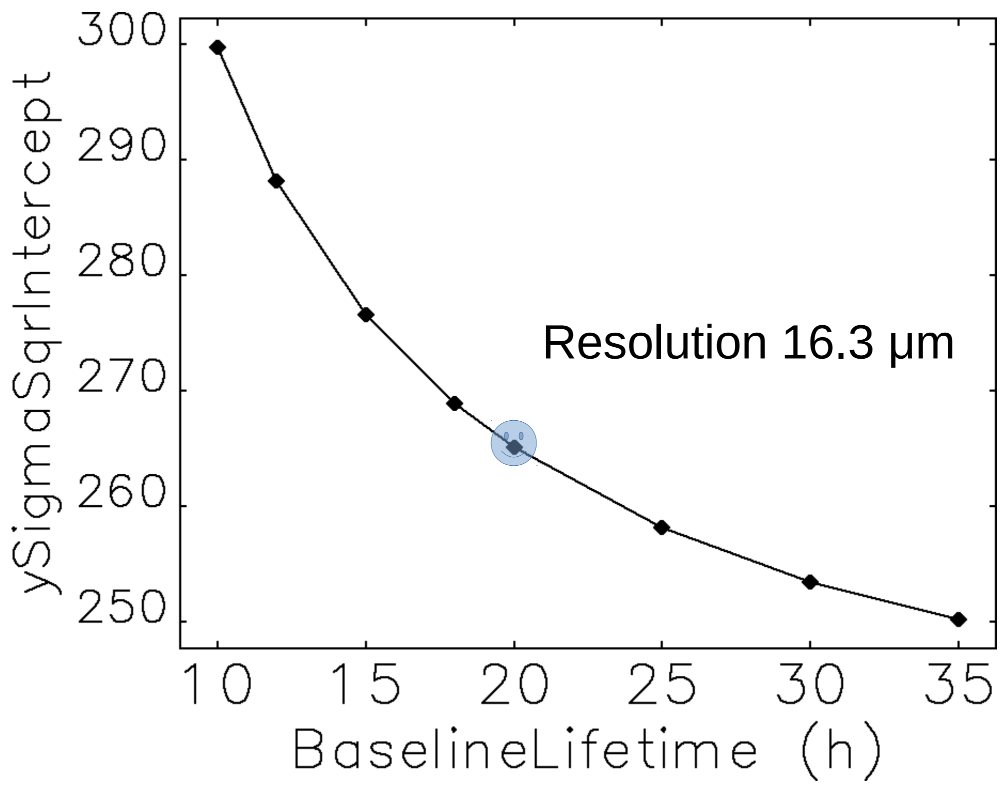
Fitting $(\tau)^2$ versus $(\sigma_y)^2$ for different baseline lifetime

- Fitting result with various gas scattering lifetime (I=25 mA, δ_{acc} ~ 1.2%)
- Select baseline which gives straight line.



Resolutions determined from intercepts

- Resolution of 16.3 um give a minimum vertical emittance of 3.5 pm for the optics used.
- 16.3 um resolution itself gives an apparent vertical emittance of 6.4 pm
- A measurement using different chromaticity and sextupole configuration gives 15.5 um resolution. Gives an idea of the uncertainty in resolution.
- At this point one can start benchmarking short lifetime with Vrf, chromaticity, etc



Conclusion

- Some measurement and simulations at 6 GeV have begun
- Obviously completion of some beam measurements must precede other measurements
  - e.g. understanding single bunch limit before measuring multi-bunch limits, circumventing of HOM at high current, pinhole resolution
- Interesting behavior of single bunch instability threshold as a function of ξ_y