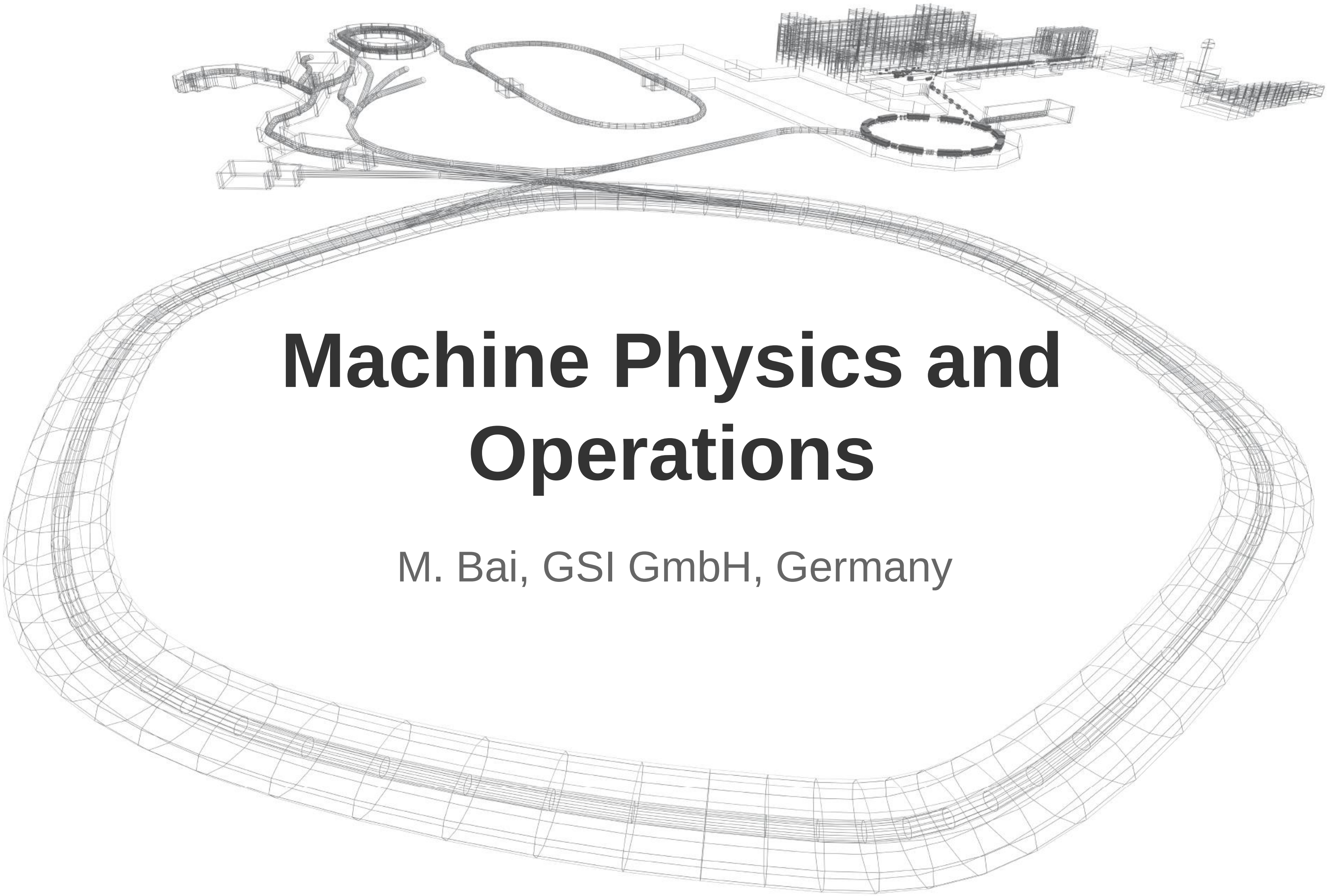
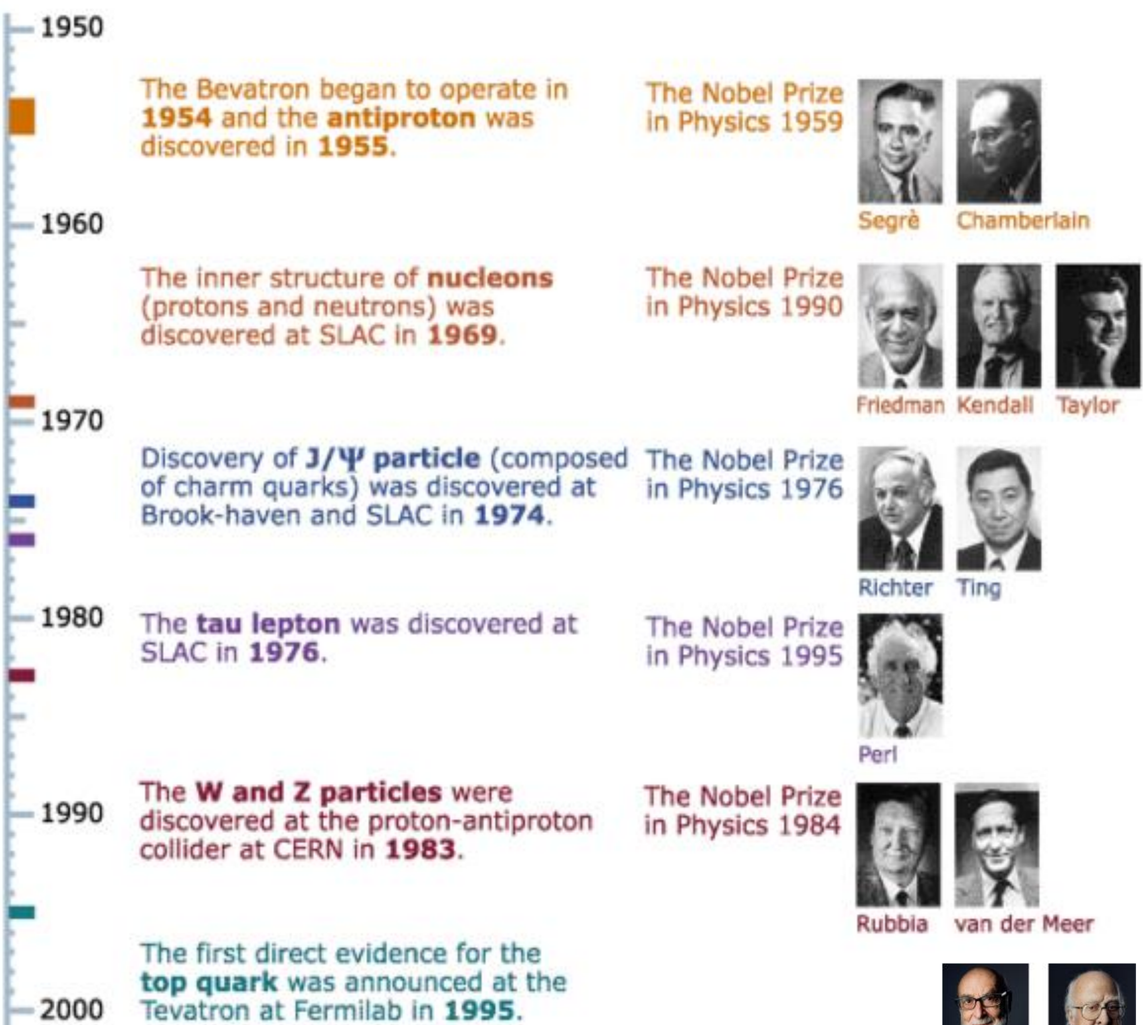
Machine Physics and Operations

M. Bai, GSI GmbH, Germany



The accelerator operations' Holy Grail:

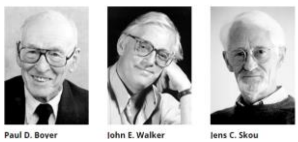
fulfill the scientific goals for the users



2012 Discovery of Higgs at LHC@CERN

With synchrotron light source

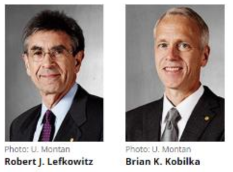
1997 For their elucidation of the enzymatic mechanism underlying the synthesis of adenosine triphosphate (ATP)



2003 for discoveries concerning channels in cell membranes, and discovery of water channels

for the discovery and development of the green fluorescent protein, GFP

2012 Reveal the structure and function of G-protein--coupled receptor



http://www.nobelprize.org/educational/physics/accelerators/discoveries-1.html

What matters for Collider Operation?

- **Luminosity! Luminosity!**

  # of collisions per unit area and per unit time

- For the case of head-on collisions

# of particles from beam 1 in collision

# of particles from beam 2 in collision

$$L = f\frac{N_1 N_2}{A}$$

Frequency of collision

Area of collision, ie the product of beam size

- Ways to increase the luminosity
  - Increase # of particles in each beam, ie bunch intensity
  - Increase # of bunches
  - Make each bunch more bright, i.e. shrink the size of the bunch at IP
  - increase luminosity lifetime

Machine physics for collider operations

- beam-beam effect
  - non-linear force, induces coherent and inconheren tune shift

$$\Delta Q = \frac{1}{4\pi}\oint \beta(s)k(s)ds$$

coherent ΔQ: $$\Delta Q = \frac{1}{4\pi}\oint \beta^* \frac{nq^2(1+\beta^2)}{4\pi\varepsilon_0\sigma^2 p} ds$$

For the case of relativistic:

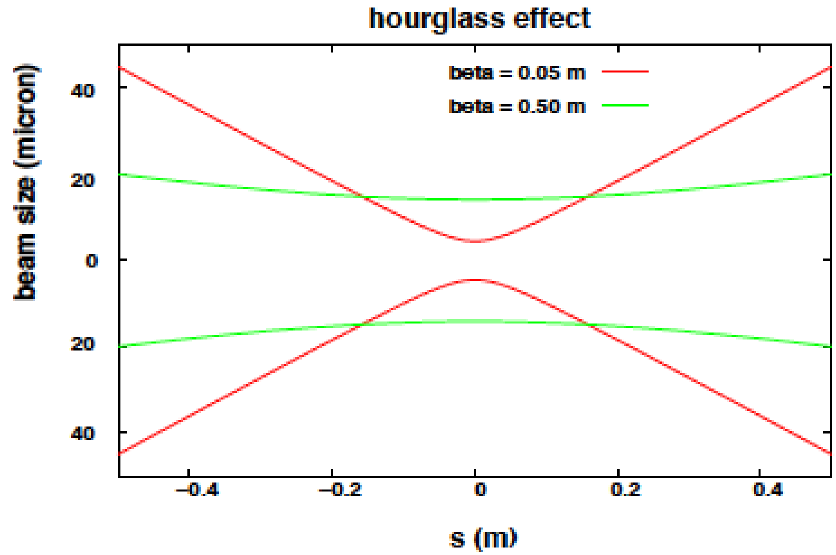
$$\Delta Q = \frac{1}{4\pi}\frac{\beta^* N}{\gamma\sigma^2}\frac{q^2}{4\pi\varepsilon_0 mc^2} = \xi$$

- The cure: e-lens to compensate the beam-beam force

X. Gu, W. Fischer et al, PHY. REVIEW ACCELERATORS AND BEAMS 20, 023501, 2017

- hour-glass effect
  - transverse beam size along the longitudinal beam

$$\sigma_s = \sigma^* \sqrt{1 + \frac{s}{\beta^*}^2}$$



$L(\sigma_s) = L(0) \cdot H$ where

$H = \sqrt{\pi} u_x e^{u_x^2} \operatorname{erfc}(u_x)$ and $u_x = \beta^*/\sigma_s$

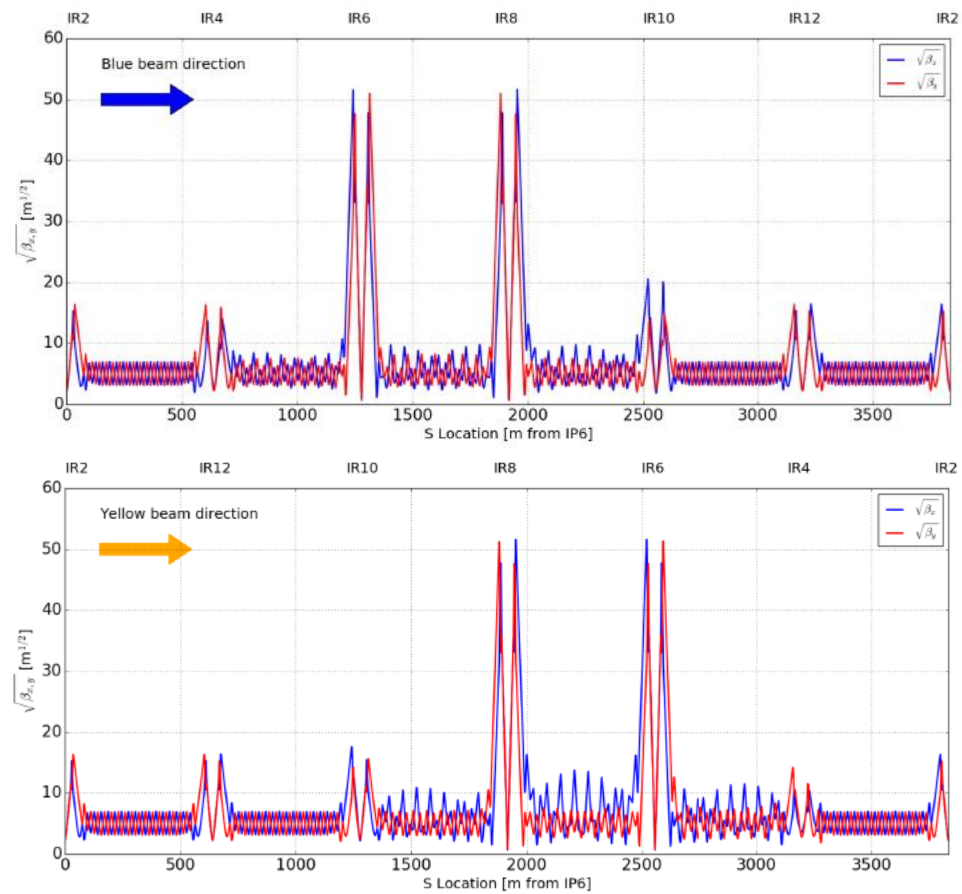
Machine physics for collider operations

- beam cooling in combination with dynamic beta squeeze to increase the integrated luminosity

linear optics optimization and matching

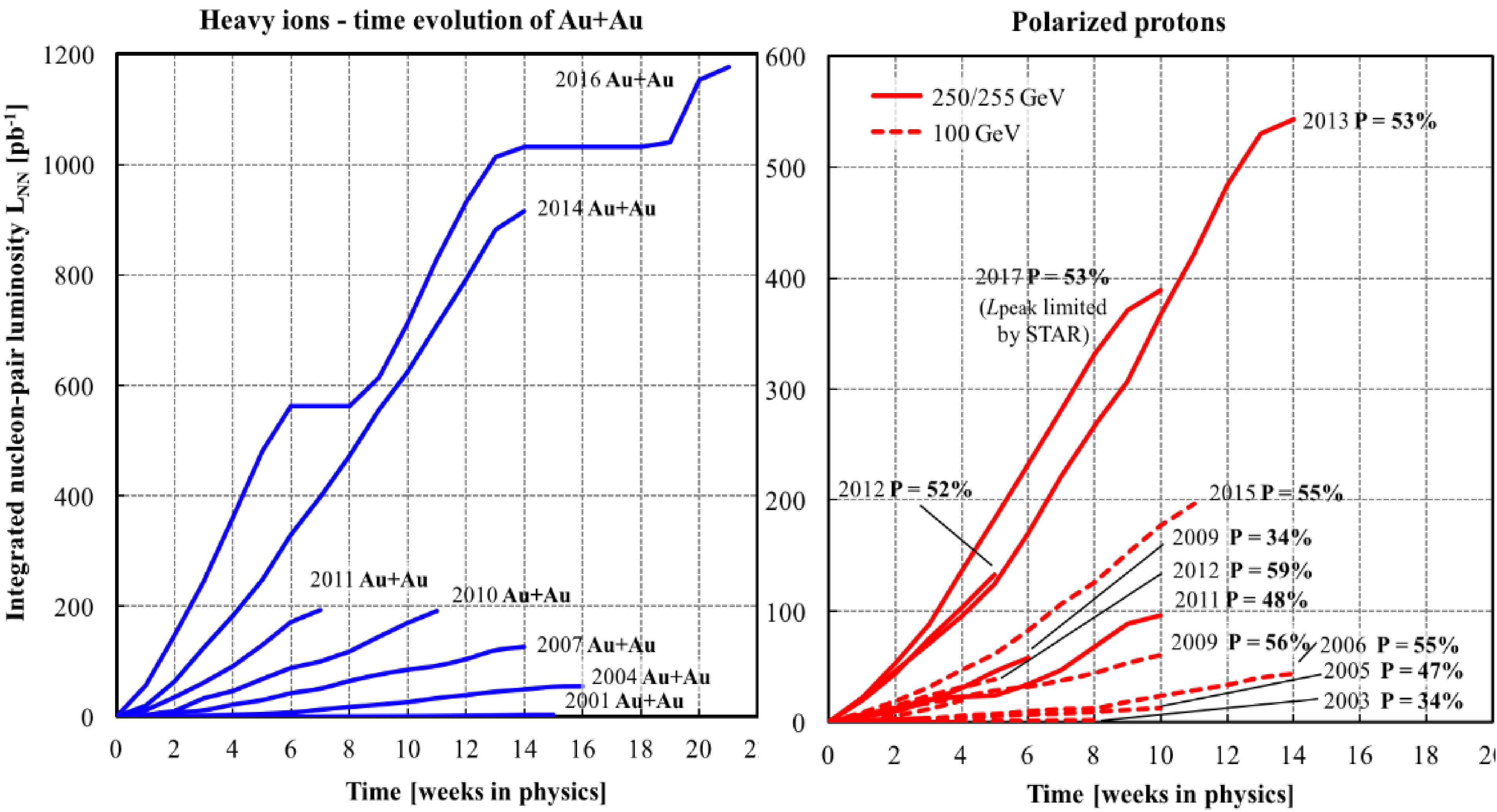
  - controlled beta beat
  - concept first raised and tested at LHC, a.k.a. Achromatic Telescope Squeezing (ATS)

$$\xi_x = -\frac{1}{4\pi}\sum_i \beta_{x,i} k_{1i} l + \frac{1}{4\pi}\sum_j \beta_{x,j} D_{x,j} k_{2j} l$$



G. Robert-Demolaize, et al.

Achieve beyond the design



W. Fischer, http://www.rhichome.bnl.gov/RHIC/Runs

Synchrotron light source operation

- **Brilliance, brilliance**

  Photons per sec per $mm^2 mrad^2$

  per bandwidth

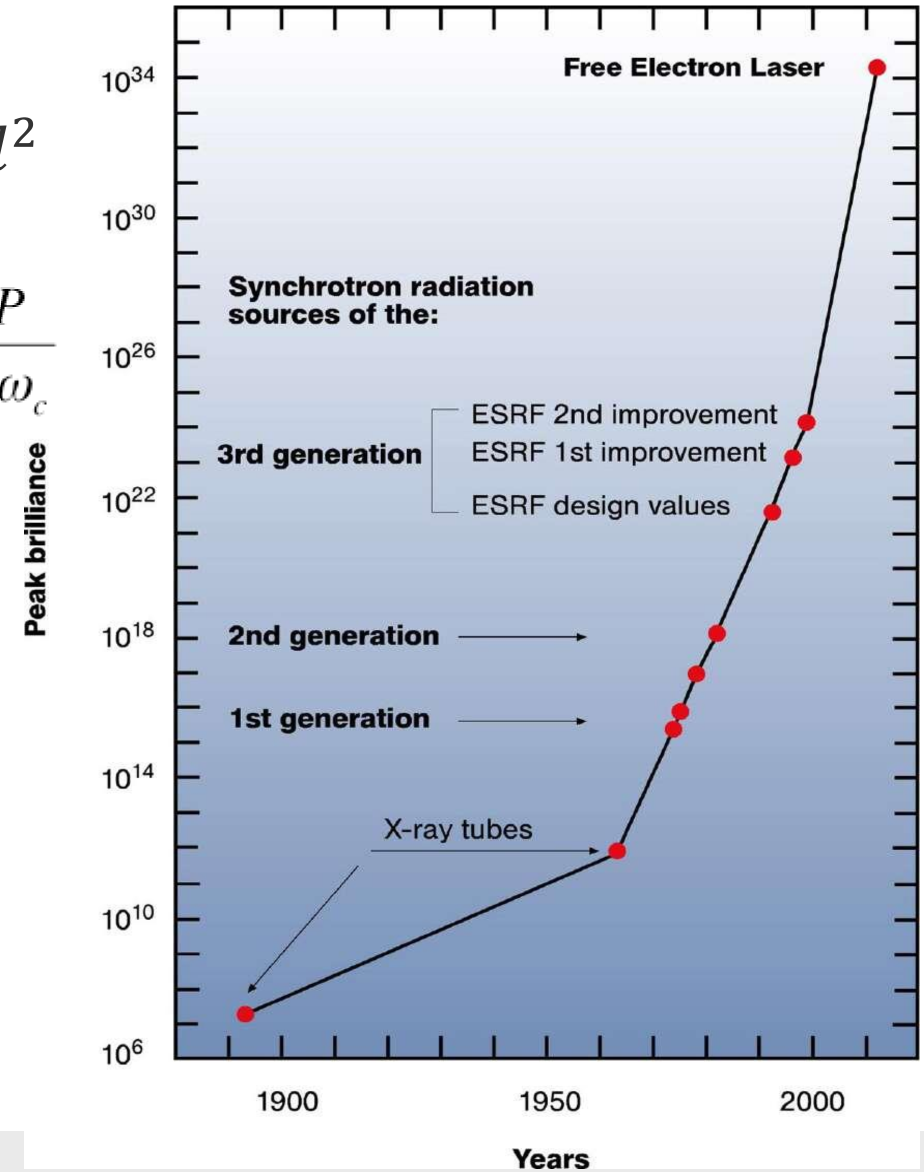
  photon flux $\dot{N} = \int \dot{n}(\omega) d\omega = \frac{15\sqrt{3}}{8} \frac{P}{\hbar \omega_c}$

$$\dot{n}(\omega) = \frac{1}{\hbar\omega}\frac{dP}{d\omega} = \frac{P}{\omega\omega_c}\frac{9\sqrt{3}}{8\pi}\frac{\omega}{\omega_c}\int_{\frac{\omega}{\omega_c}}^{\infty} K_{5/3}(x)\,dx$$

critical frequency $w_c = \frac{3}{2}\frac{c}{r} g^3$

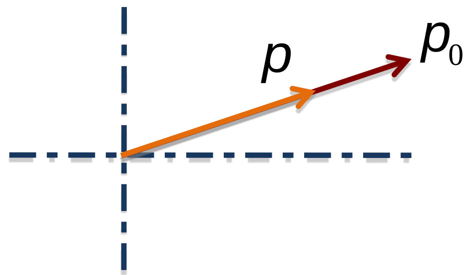
- The smaller beam emittance,

  the brighter the light!



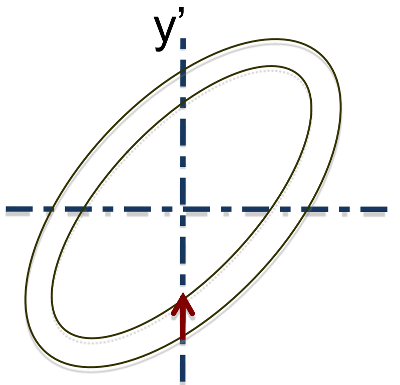
Machine physics for collider operations

- Beam emittance in an electron storage ring is determined by synchrotron radiation induced damping as well as quantum excitation
- Synchrotron radiation damping



$$p_y \approx p_{y,0}\left(1 - \frac{dp}{p_0}\right)$$

$$\frac{d\varepsilon_y}{dt} = -\varepsilon_y \oint \frac{dp}{p_0} / T_0 \approx -\frac{U_0}{E_0 T_0}\varepsilon_y$$

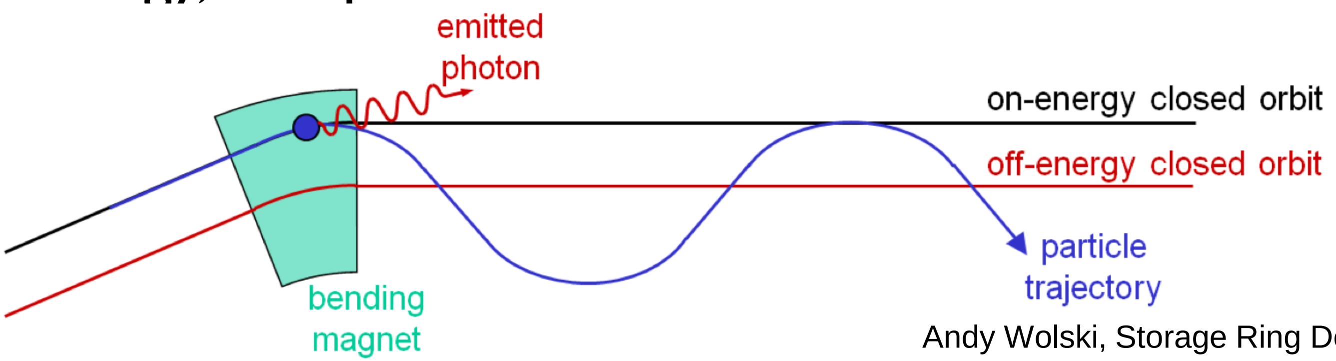


$U_0 = \oint P_\gamma \, dt = \frac{C_\gamma}{2\pi} E_0^4 \oint \frac{1}{\rho^2} ds$ is the energy loss per turn, and

$I_2 = \oint \frac{1}{\rho^2} ds$ is the second synchrotron radiation integral

Machine physics for collider operations

- The energy loss due to the emitted photon excites an horizontal betatron oscillation around the closed orbit corresponding to its new energy, aka quantum excitation



Andy Wolski, Storage Ring Design

- As a combination of damping and quantum excitation, $\epsilon_x = C_q \frac{\gamma^2}{j_x} \frac{I_5}{I_2}$

with $\frac{d\epsilon_x}{dt} = -\frac{2\epsilon_x}{\tau_x} + \frac{2}{j_x \tau_x} C_q \gamma^2 \frac{I_2}{I_5}$ and $C_q = \frac{55}{32\sqrt{3}} \frac{\hbar}{mc} \approx 3.832x10^{-13}$ m

and $j_x = 1 - \frac{I_4}{I_2}$ where $I_4 = \oint \frac{\eta_x}{\rho} \left(\frac{1}{\rho^2} + 2 \frac{\partial B_y / \partial x}{B\rho} \right) ds$ and $I_5 = \oint \frac{H_x}{\lfloor \rho^3 \rfloor} ds$

where $H_x = \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta_{px} + \beta_x \eta_{px}^2$

- to obtain small natural emittance: minimize H function
  - Lattice choices: FODO, DBA, TBA, MBA

Lattice	Minimum emittance	conditions
90^o FODO	$\approx 2\sqrt{2}C_q\gamma^2\theta^3$	$\frac{f}{L}=\frac{1}{\sqrt{2}}$
137^o FODO	$\approx 1.2C_q\gamma^2\theta^3$	Minimum for FODO
DBA	$\approx C_q\gamma^2\frac{1}{4\sqrt{15}}\theta^3$	at end of dipole $\eta_{x,px}=0$; $\beta_x\approx\sqrt{12/5}L$; $\alpha_x\approx\sqrt{15}$
TME	$\approx C_q\gamma^2\frac{1}{12\sqrt{15}}\theta^3$	$\eta_{x,\min}\approx\frac{L\theta}{24}$; $\beta_{x,\min}\approx\frac{L}{2\sqrt{15}}$
MBA	$\approx C_q\gamma^2\frac{1}{12\sqrt{15}}\left(\frac{M+1}{M-1}\right)\theta^3$	2 < M < infinity

Andy Wolski, Storage Ring Design

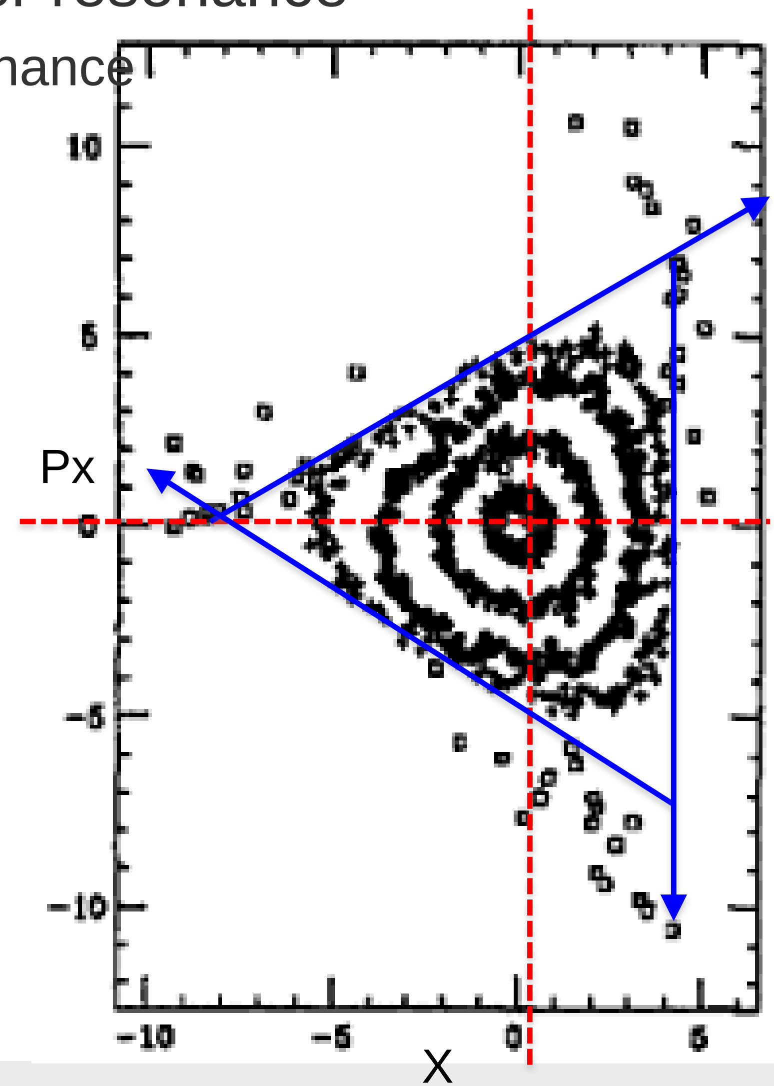
Machine physics for fixed target operations

- slow beam extraction using 3rd order resonance
  - In the presence of sextupole field, a resonance can be excited if the betatron tune
  - the three unstable fixed points (x,Px) are

$$\left(-\frac{8\pi\Delta Q}{A}, 0\right) \text{ and } \left(\frac{4\pi\Delta Q}{A}, \pm\sqrt{3}\frac{4\pi\Delta Q}{A}\right)$$

where $\Delta Q = Q - k/3$ and

$$A \propto \oint k_2 \cos\left(3Q\phi(s)\right) ds$$

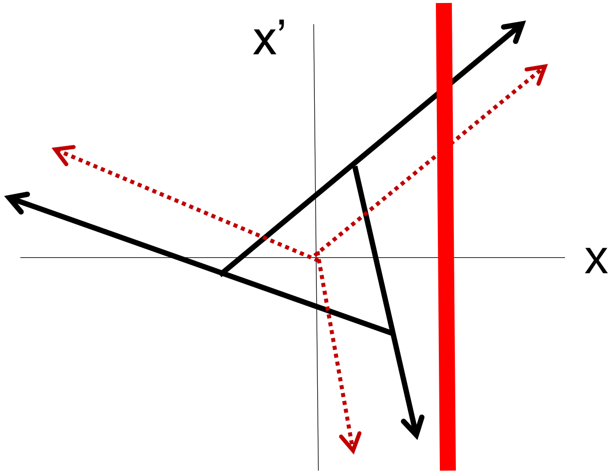


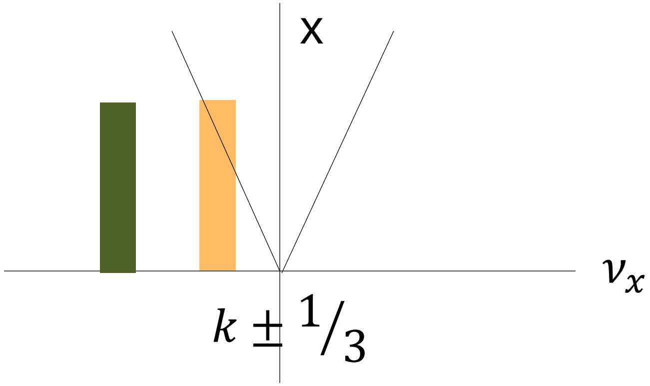
- Along the separatrix at $x = \frac{4\pi\Delta Q}{A}$

$$\frac{dp_x}{dn} = \frac{1}{4}Ap_x^2 - \frac{3}{4}x^2$$

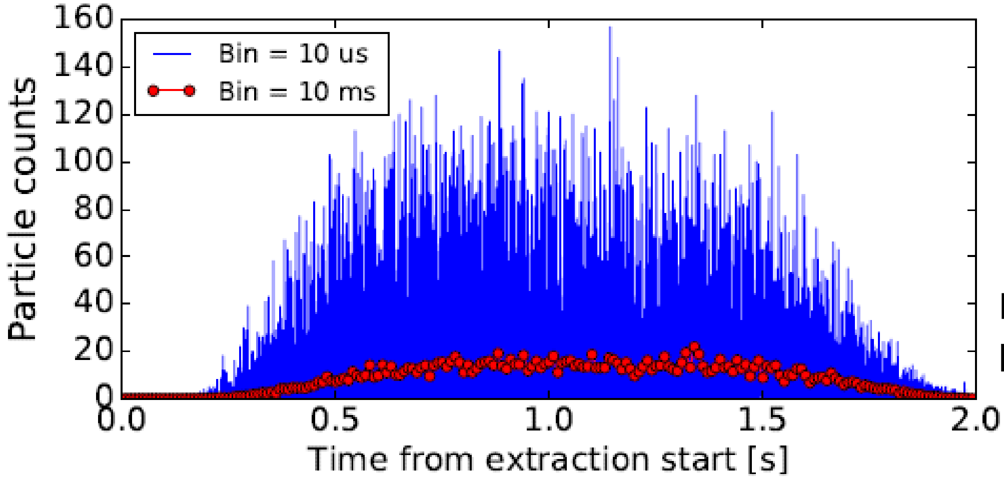
Machine physics for fixed target operations

- Typical slow extraction technique: using 3rd order resonance





- To have desired smooth uniform slow extraction rate free of sporadic behaviors has been the main challenges in many facilities

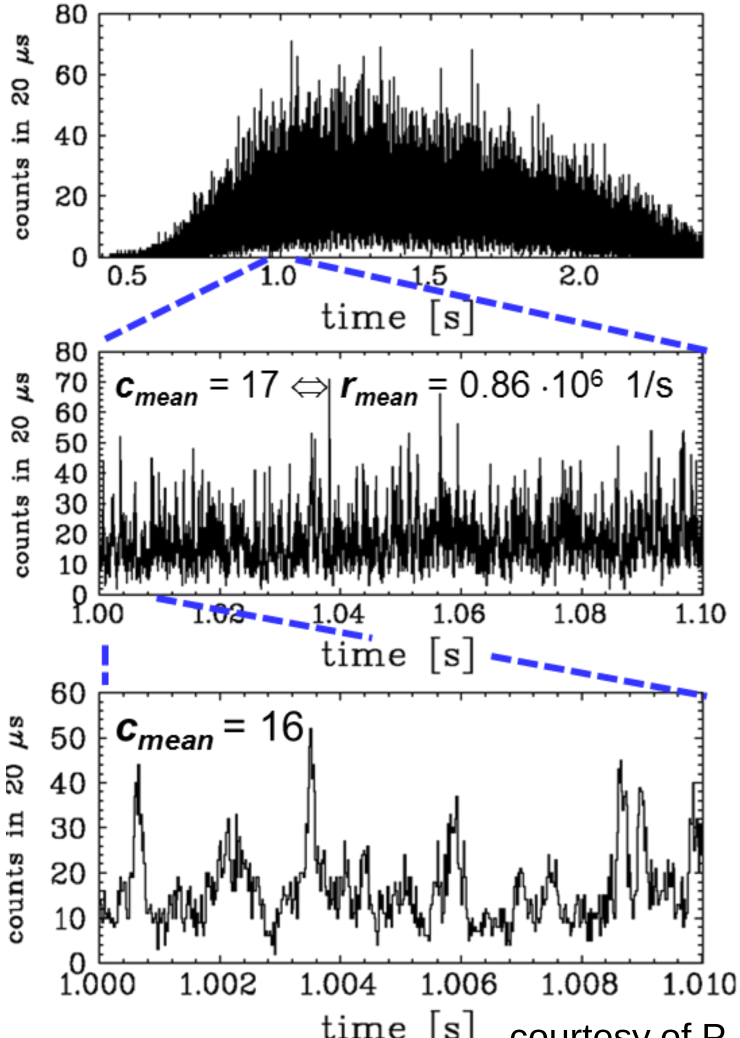


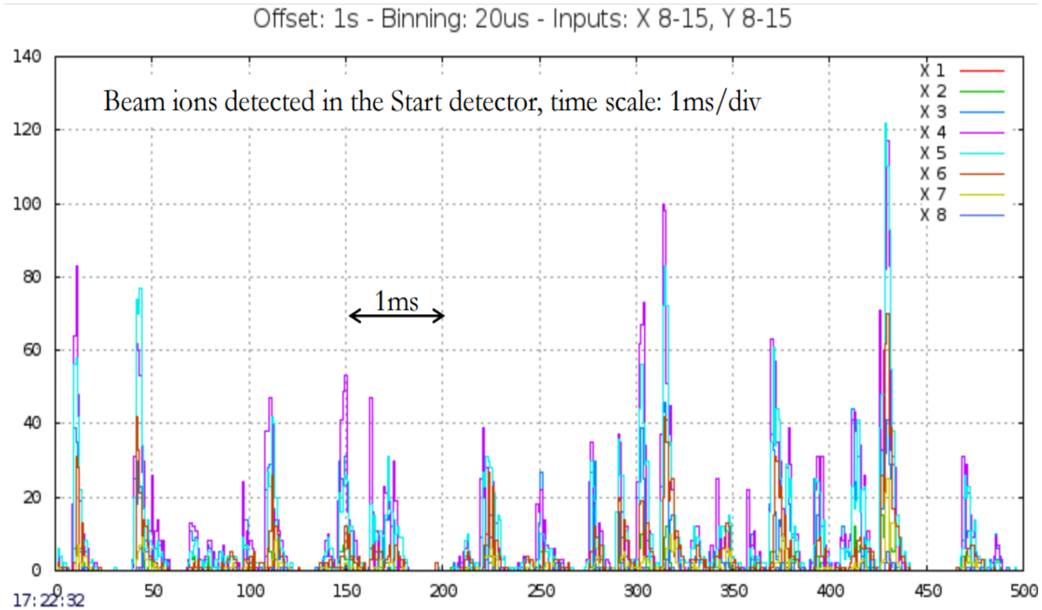
R. Singh et al, IPAC2018 proceeding, WEPAK007

SIS18 Slow Extraction Beam Quality

- micro spill structure

courtesy of HADES



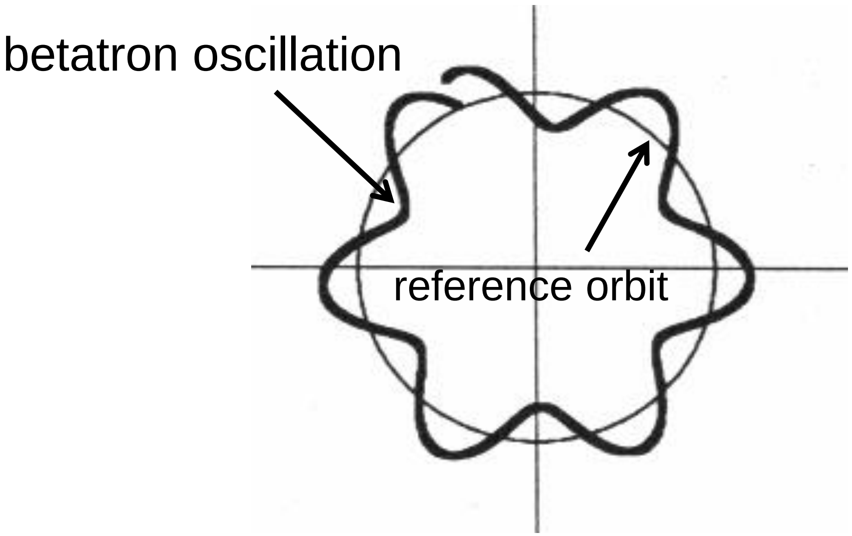


- spill structure measured by HADES detector
- This posts significant degradation of the detector efficiency in terms of
  - **substantial reduction of acquired statistics**
  - **higher risk of tripping detectors**

courtesy of P. Forck and SIS18 team

Machine physics for fixed target operations

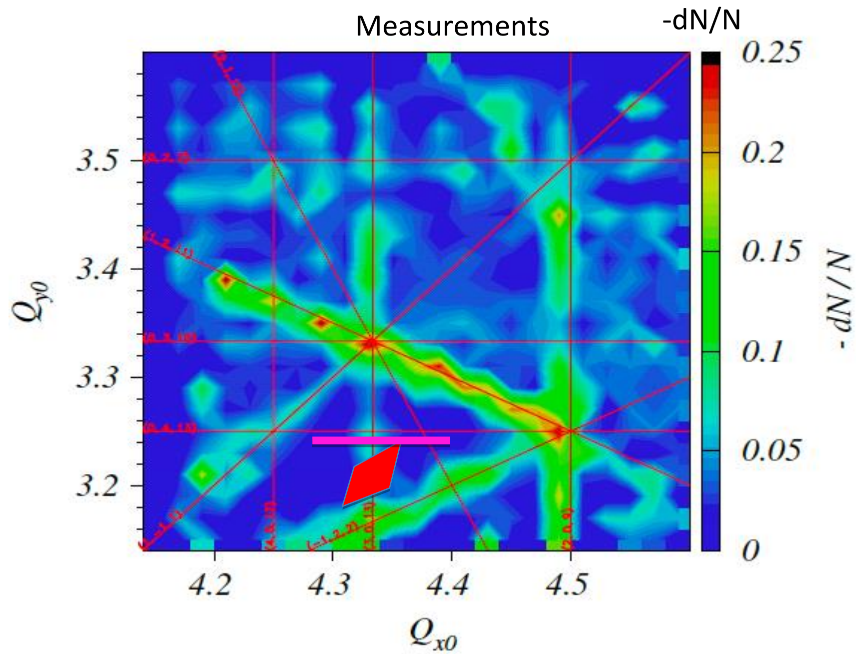
- lattice resonances due to structure, as well as errors
  - frequency of particle motion coincides with the periodicity of the structure and distribution of various errors
  - SIS18: first systematic experimental resonance charge diagram



betatron tune $Q_{x,y}$: # of oscillation in one orbital turn

Resonance condition: $kQ_x+mQ_y=n$

Tune scan at SIS18

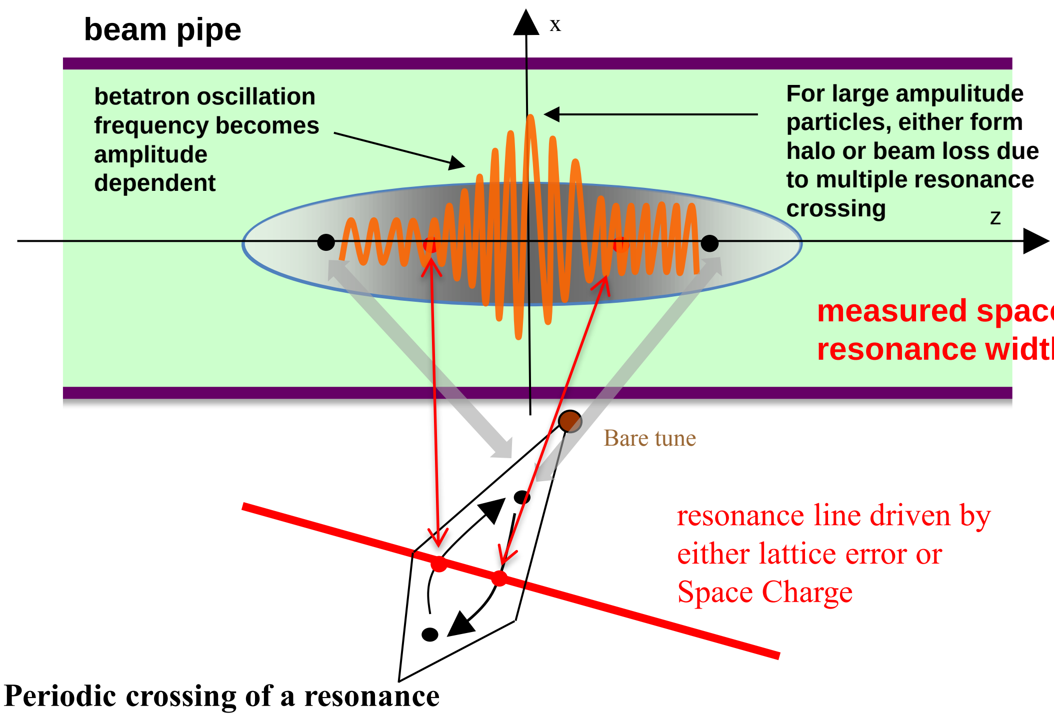


G. Franchetti et al., GSI-Acc-Note-2005-02-001

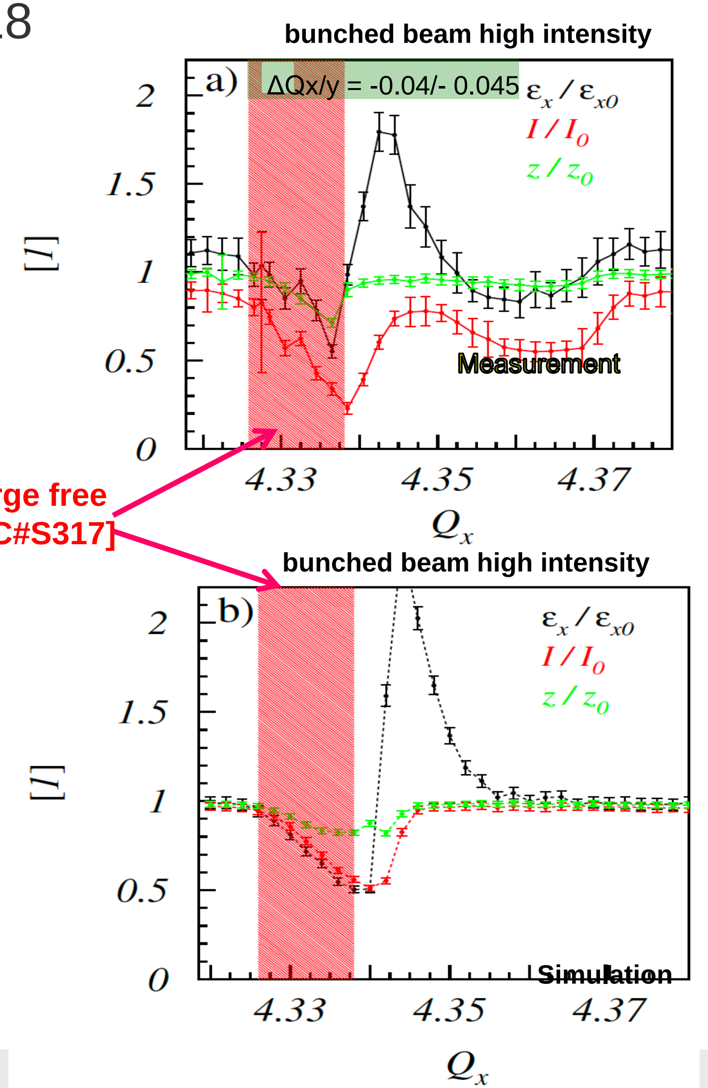
Courtesy of G. Franchetti

Machine physics for fixed target operations

- coupling of space charge with lattice resonances [PAC#S317]
  - complete experimental confirmation at SIS18
  - **Excellent agreement w. simulation!!!**



measured space charge free resonance width [PAC#S317]

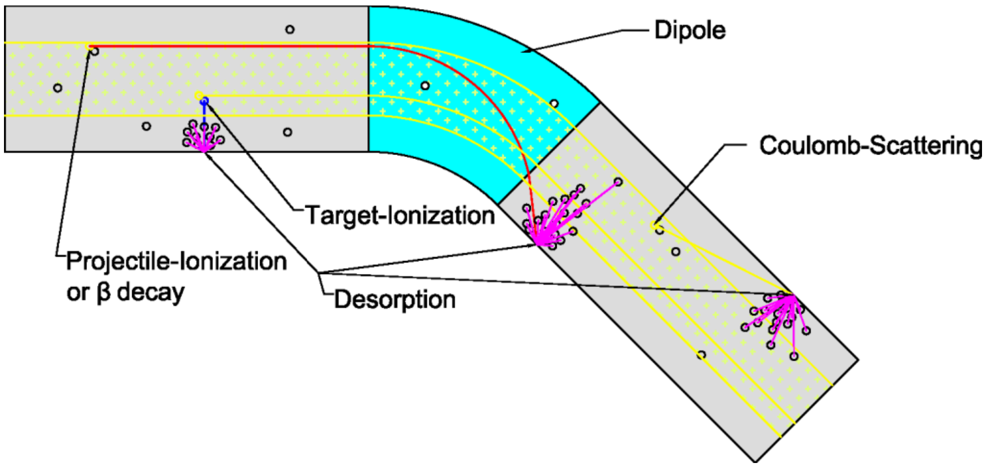


Courtesy of G. Franchetti

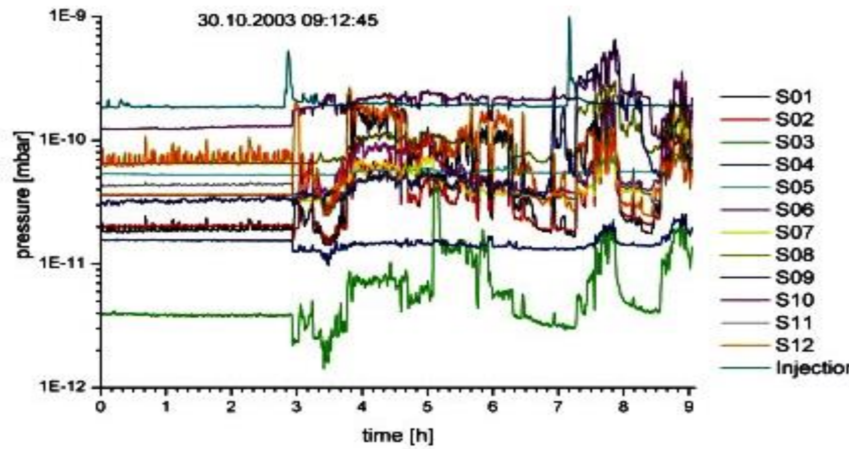
Machine physics for fixed target operations

- High intensity heavy ion beams: dynamics vacuum instability

beam induced desorption

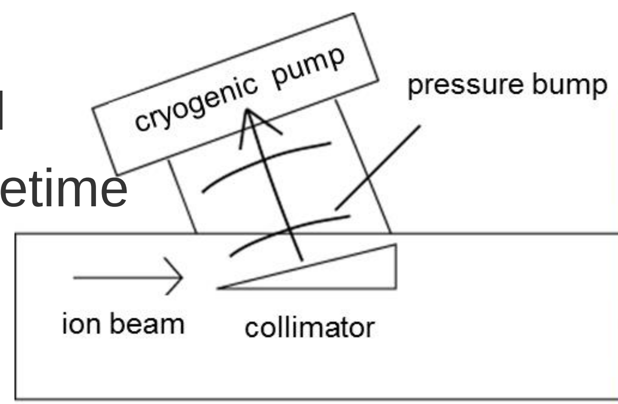


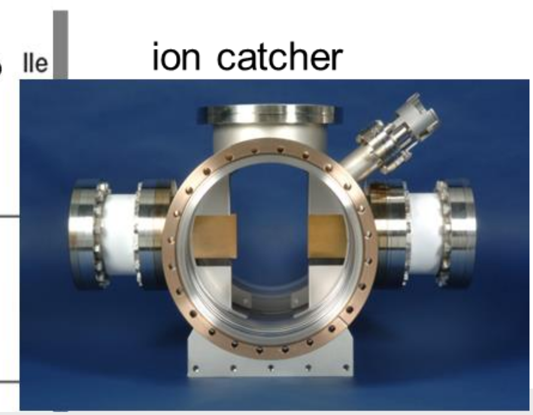
SIS18 vacuum during high intensity operation



- Cryogenic-pump to mitigate the dynamic vacuum instability
  - significant increase of initial beam intensity and beam lifetime
  - world record intensity of U^{+29} beam

Courtesy of P. Spiller





My humble thoughts

- Machine physics is the fundamental for the accelerator operations. The further advance of the machine physics continues to push the scope of the accelerator operations

- Nevertheless, the performance of the operation also highly depend on its reliability and availability

$$delivered = \frac{1}{t_{user} + t_{between} + t_{beamstudy} + t_{downtime}} \int_0^{t_{user}} FOM(t)dt$$

  - **Reliability:** reliably deliver the required beam to the user
    - minimize the downtime due to hardware failures

  - **Availability:** percentage of the user time to calendar/scheduled time
    - Schedule and planning to keep the balance

My humble thoughts

- Reliability and availability are also user community dependent. While 2-hour of downtime
  - may not be a big perturbation for a collider experiment
  - can be a big impact for a week long fixed target experiment
  - is absolutely devastating for a 8-hour light source user

- The right balance is essential for reaching the holy grail of the operation for user communities
  - proper maintenance, spare parts, and continuity of expertise
  - machine/beam study is healthy and beneficial if
    - the goal and technical readiness are well justified and feasible
    - well planned beforehand and end of study rule, i.e. restoring operation settings
    - Empower the operations team to be part of the study
  - compromise between peak performance and stable operation

Accelerator Operations