Beta Beams, EUROnu WP4

SEVENTH FRAMEWORK PROGRAMME

Collective Beta Beams

Christian Hansen

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Many thanks to: E. Benedetto, A. Chancé, E. Metral, N. Mounet, G. Rumolo, B. Salvant & E. Wildner

Outline

- Beta Beam Overview
- Collective Effects
  - Laslett's Tune Shifts
  - Wakefield Instabilities
    - HEADTAIL & MOSES
    - Intensity Thresholds
- Conclusion

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Beta Beams - Overview

P. Zucchelli

- **Basic idea (*Phys. Let. B, 532 (2002) 166-172*):**
  - **Accelerate radioactive ions to high γ**
  - **Let them β-decay in a Decay Ring (DR)**
  - **The DR has one straight section pointing in the direction of a neutrino detector →**
  - **ν-beam with opening angle 1/γ and with known energy and ν-species**

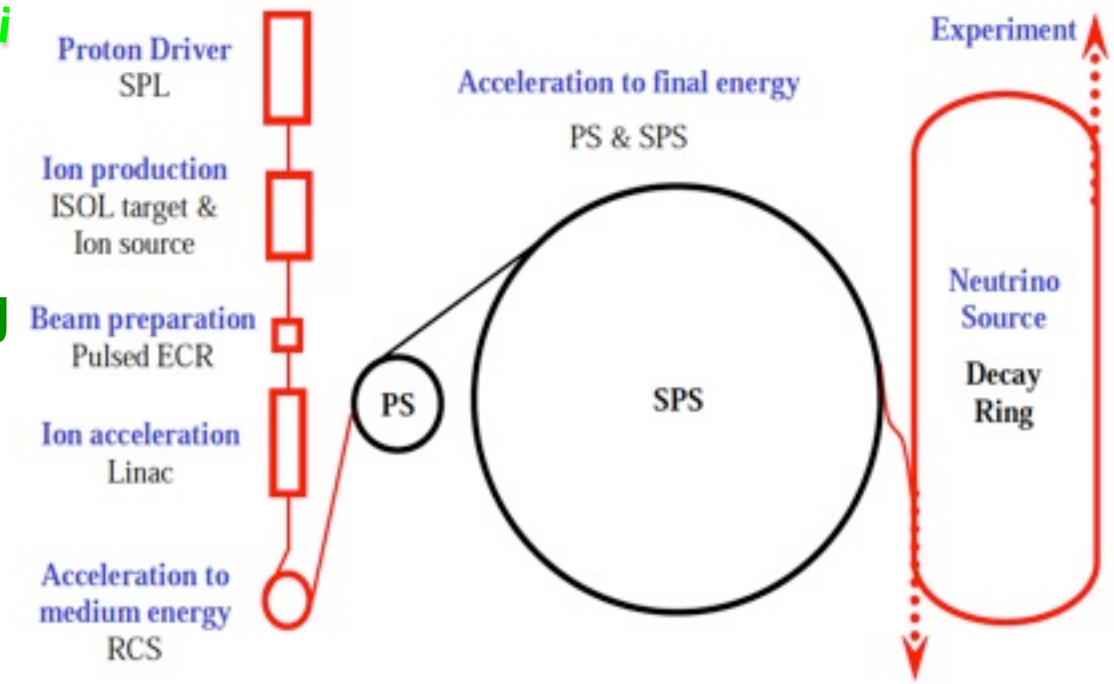
This gives only (anti) neutrinos from β^+ (β^-) decay:

$$n \longrightarrow p + e^- + \bar{\nu}_e$$

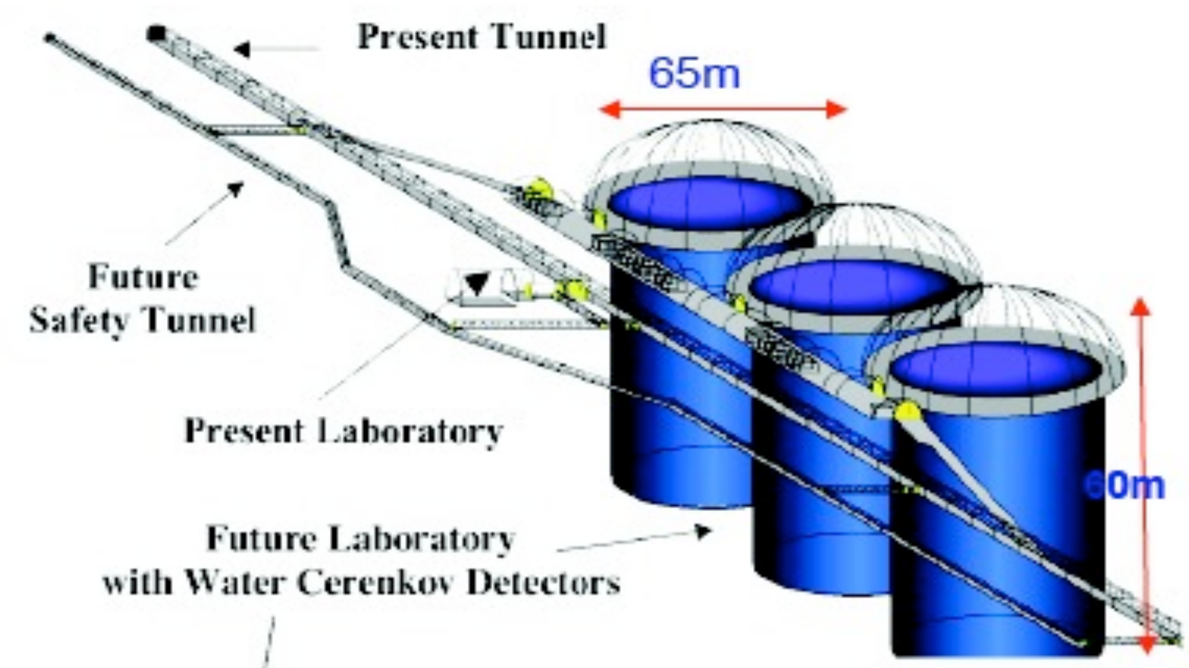
$$\text{Signal: } \bar{\nu}_e \rightsquigarrow \bar{\nu}_\mu$$

$$p \longrightarrow n + e^+ + \nu_e$$

$$\text{Signal: } \nu_e \rightsquigarrow \nu_\mu$$



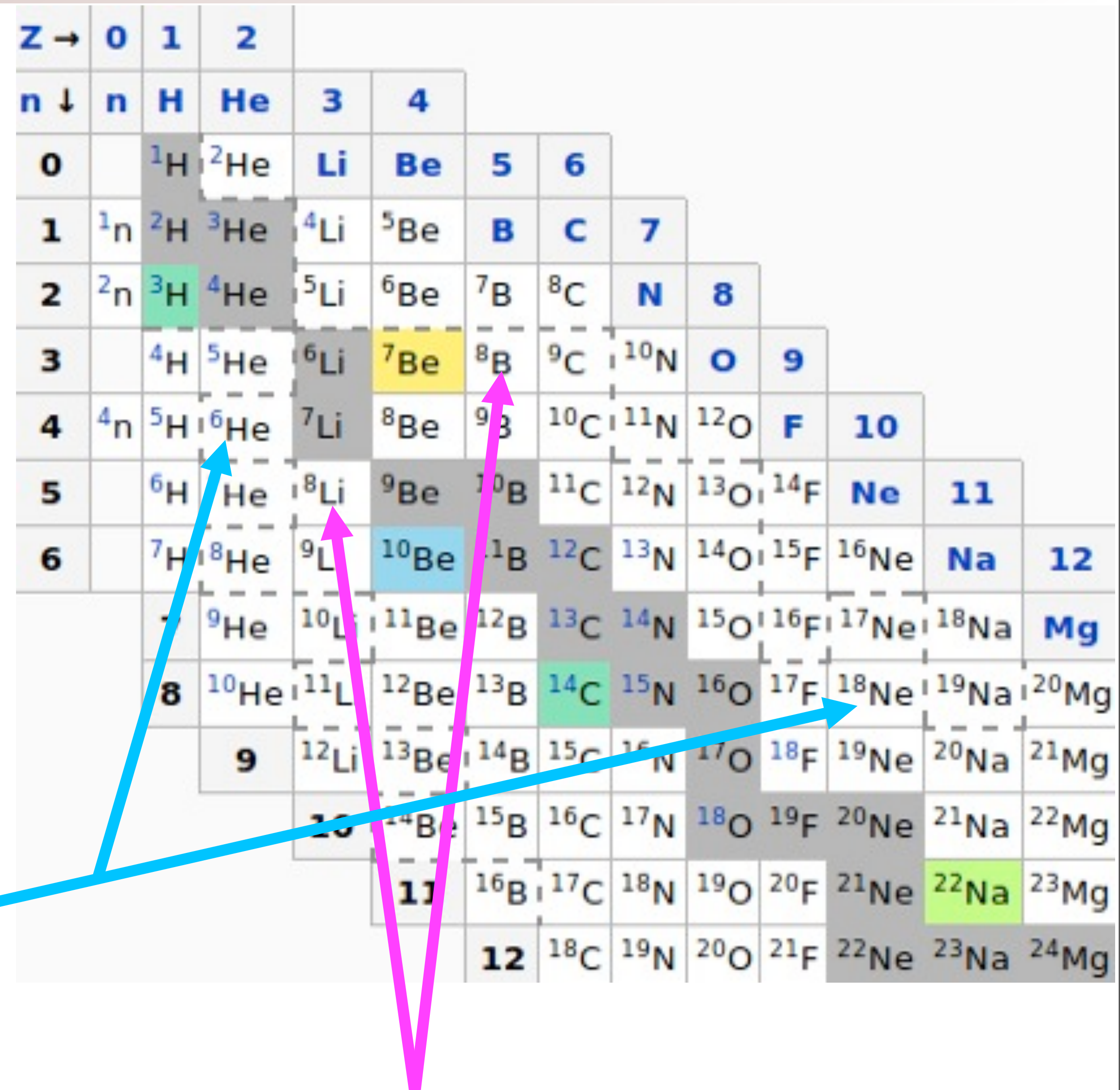
- **Detector:**
  - **Water Cerenkov detector enough to distinguish μ^+ and e^+ (μ^- and e^-), no need to distinguish μ^+ and μ^-**



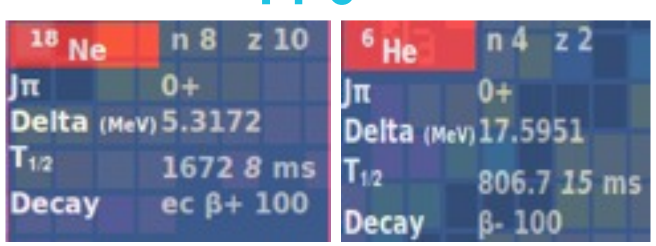
Choice of Ions

BB OVERVIEW

- **Considerations**
  - **Pair of β^+ and β^- active ions**
    for ν and anti-ν …
  - **Production rates**
    isol method or production ring
  - **Life time**
    optimized for baseline ~1s
  - **Reactivity**
    noble gases are good
  - **Q value**
    defines ν-energy & baseline
  - **Low Z preferred**
    minimize accelerated mass per charge
    reduce space charge problems



FP6

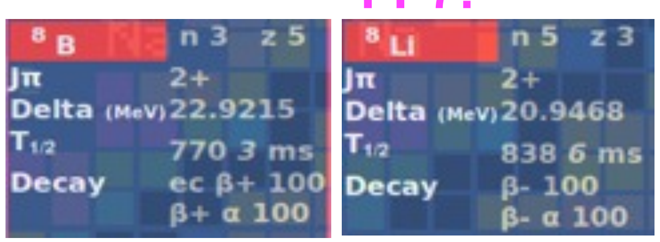


Q = 3.30 MeV Q = 3.51 MeV

FP6: EURISOL
(CARE, contract number RII3-CT-2003-506395)

EURISOL

FP7:



Q = 13.9 MeV Q = 13.0 MeV

FP7: EUROnu
(Grant agreement no.: 212372)

"Q value" is the kinetic energy release of a particle at rest

E.g. for the neutron decay

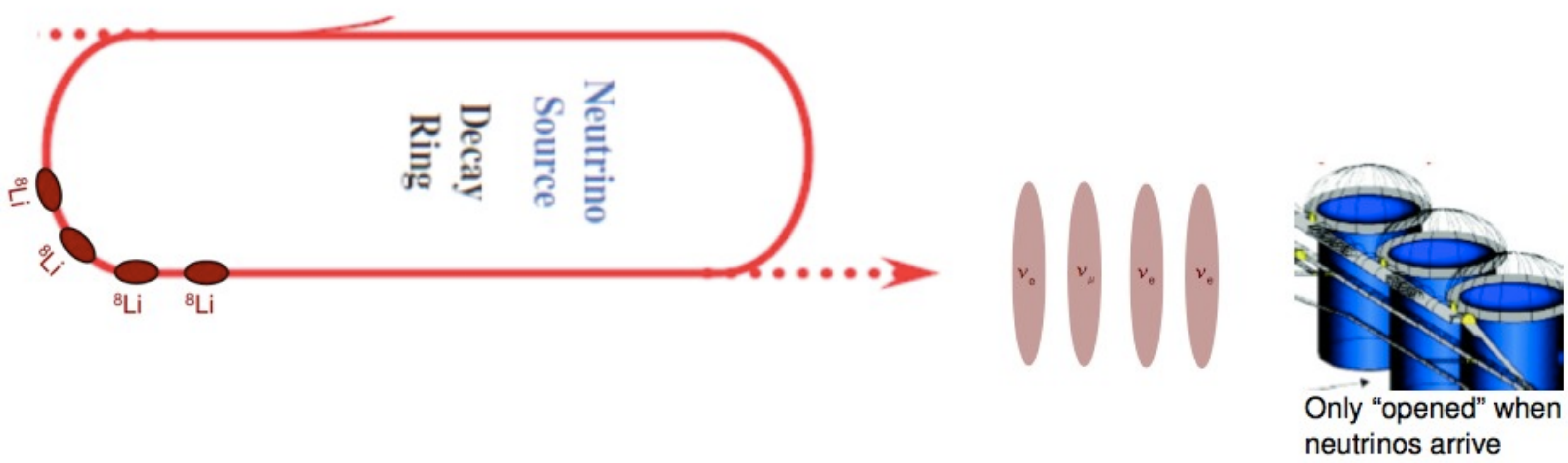
$$Q = m_n - m_p - m_{\bar{\nu}} - m_e$$

Duty Factor

BB OVERVIEW

- To suppress atmospheric background detectors can only be open short time periods
  - Suppression Factor, SF = opened time ratio of the detector
- The DR will be filled only with short bunches so that neutrinos are send only when the detector is opened
  - Duty Factor = filled ratio of the Decay Ring

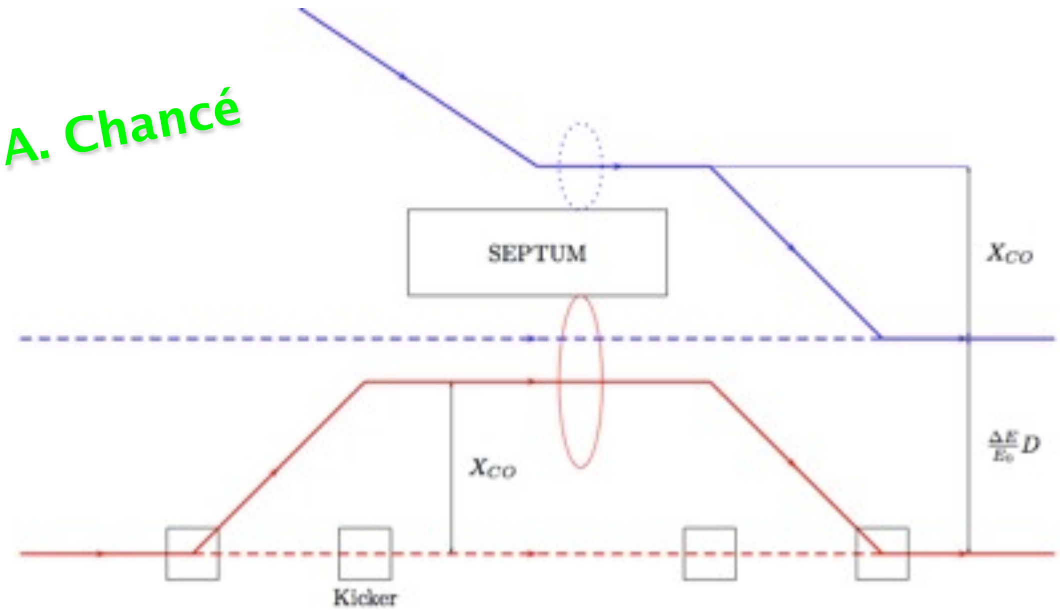
Duty Factor = Suppression Factor



DR: Injection Scheme

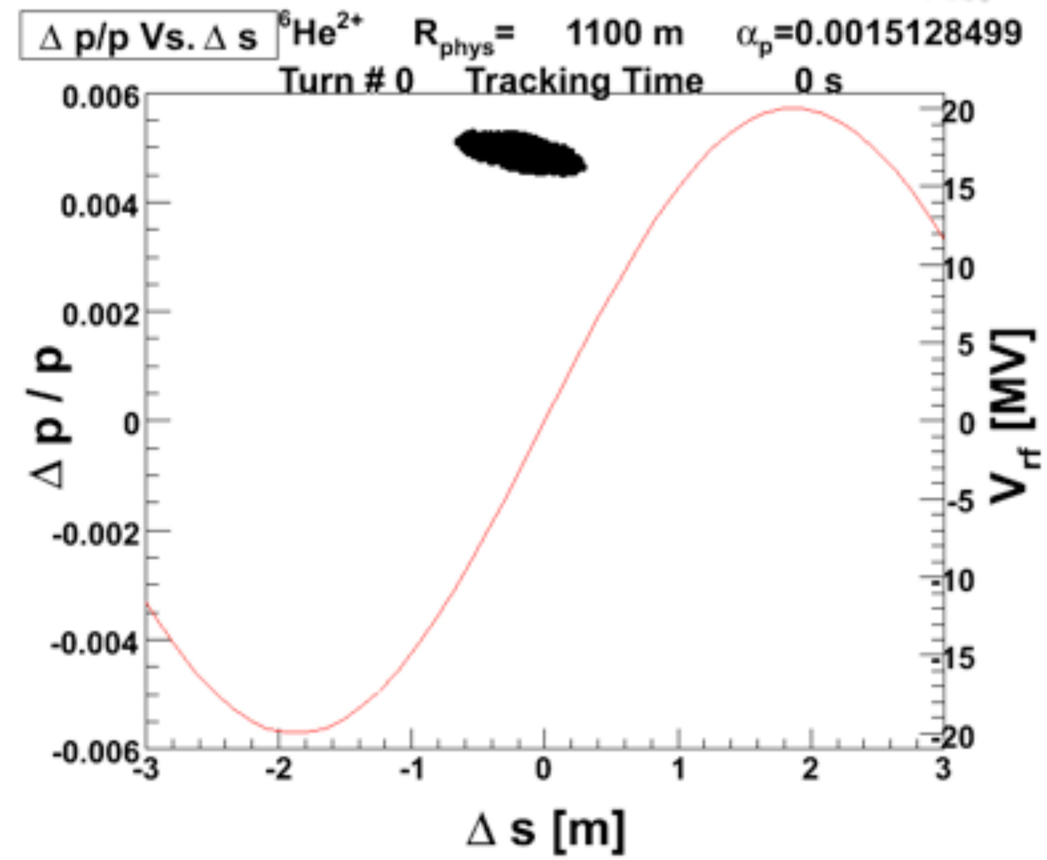
- **The new bunch is injected off momentum** (separated by a septum magnet)

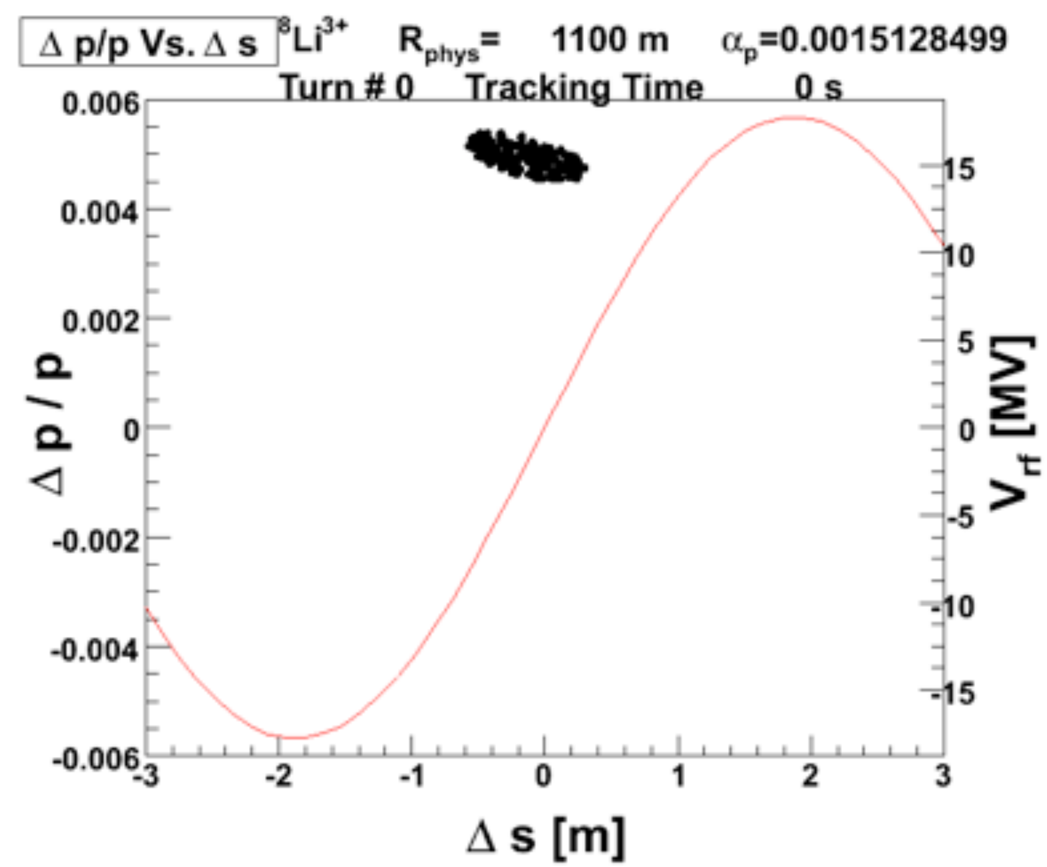
A. Chancé



- **After ¼ synchrotron turn it is "captured" by one RF system**
- **Then "merged" into the old bunch with the use of a 2nd RF system**
- **Collimation at Δp/p = 2.5‰**
  - ➡ **scrapes away ions not captured**
  - ➡ **limits the bunch size to protect the septum magnet**

Daniel C. Heinrich

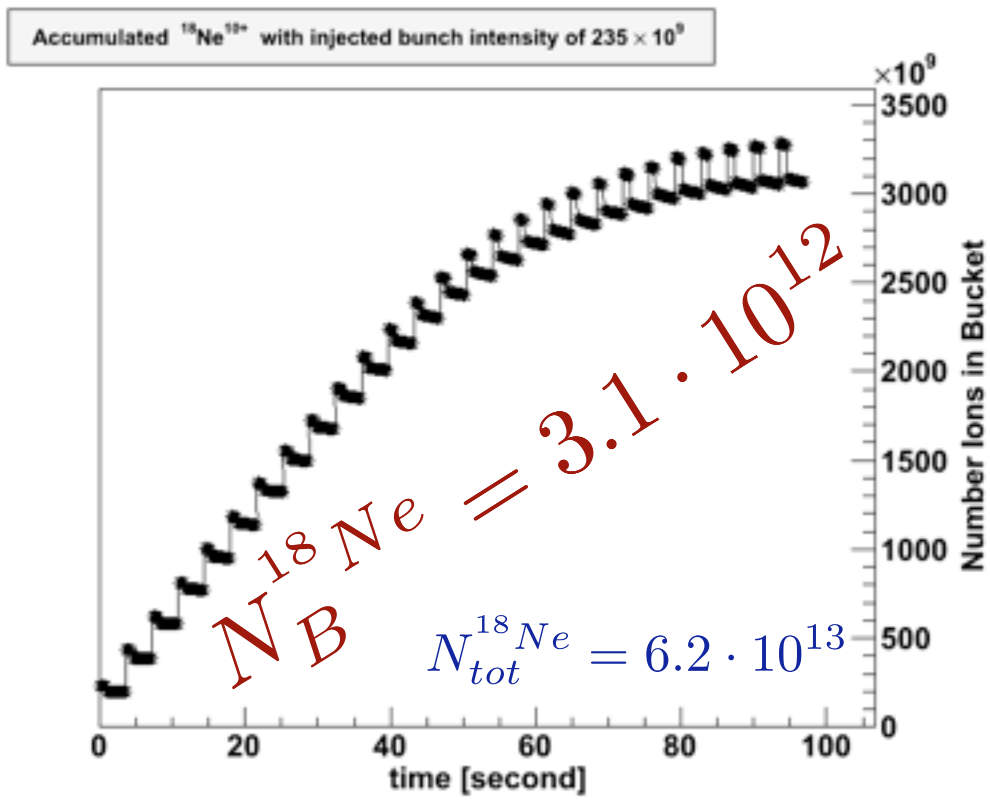


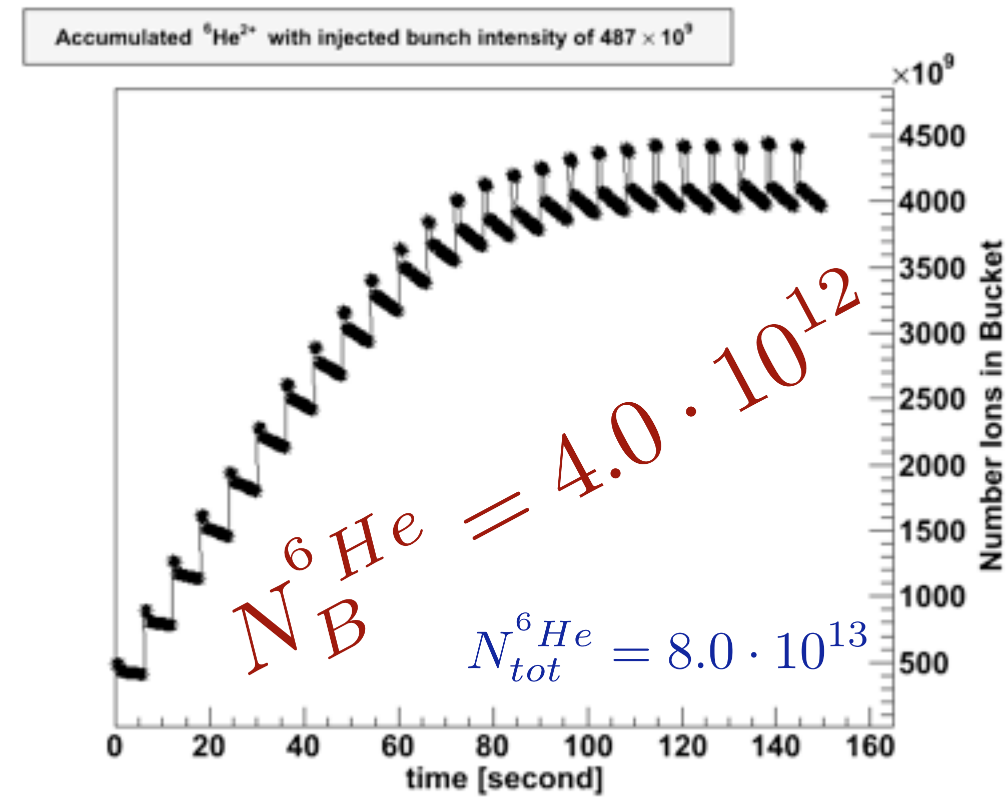


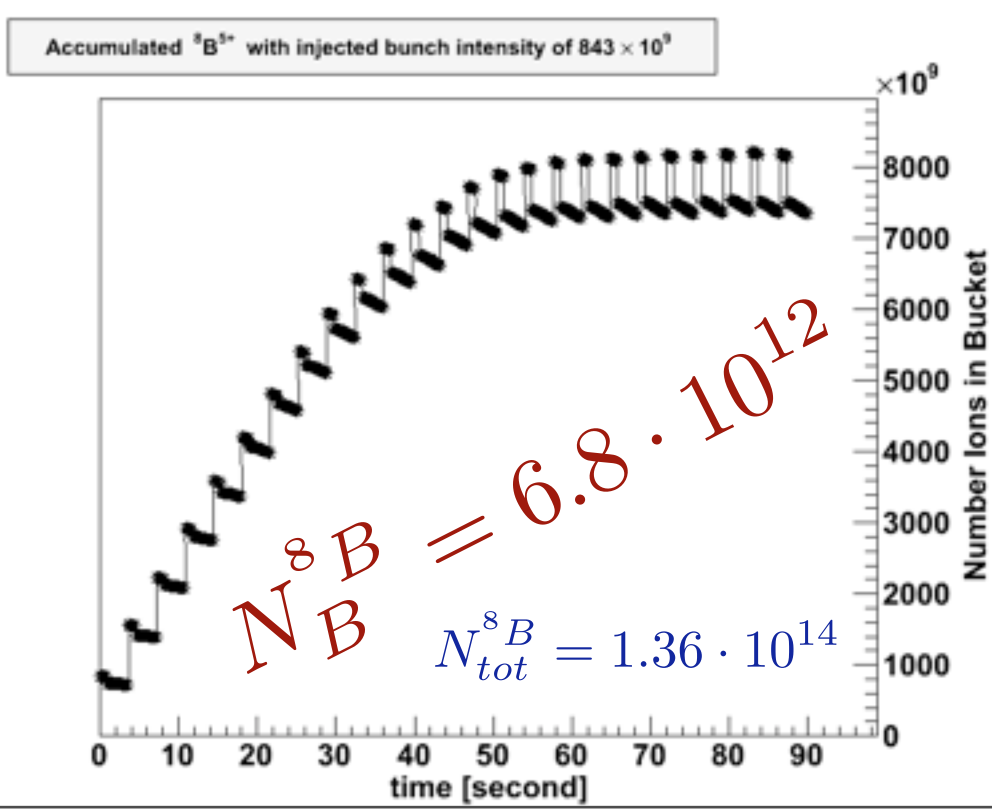
DR: Accumulation

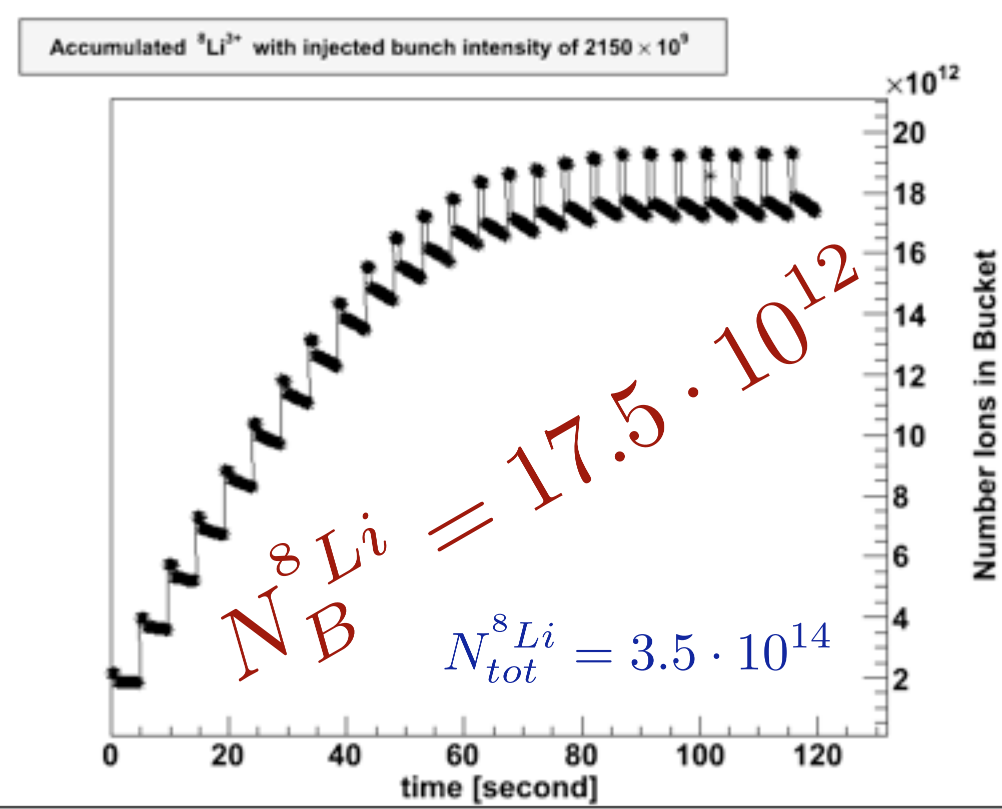
Daniel C. Heinrich

- **Due to Collimation and Radioactive decay the number of ions per bunch saturates in the DR** (20 of these bunches gives N_{tot})



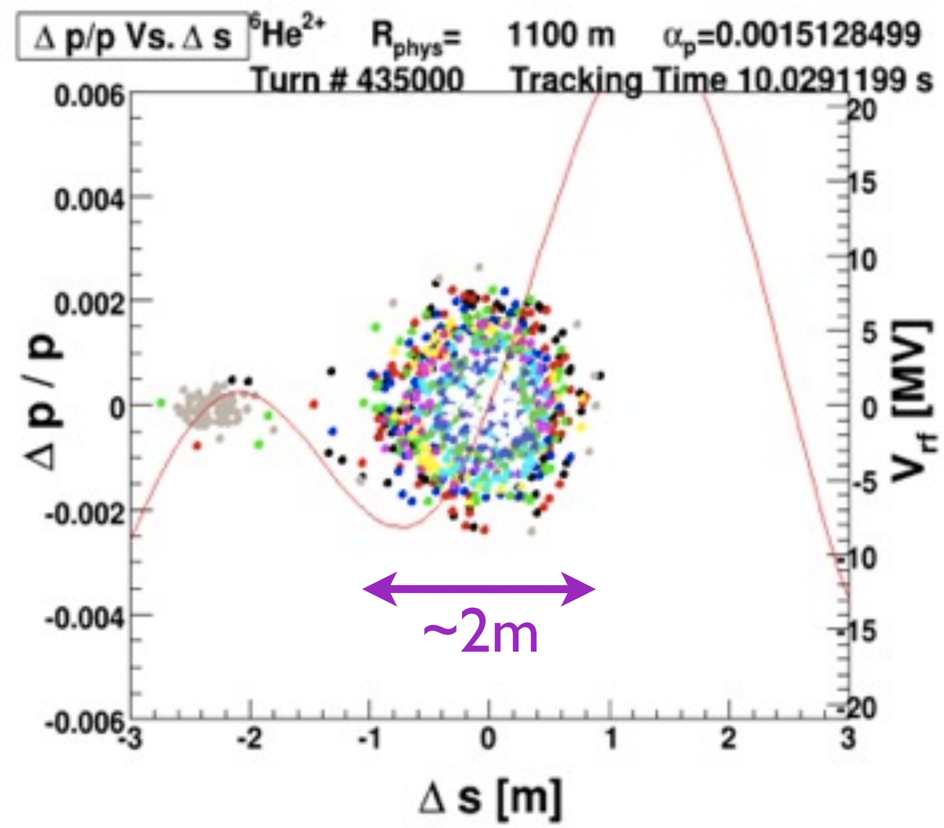




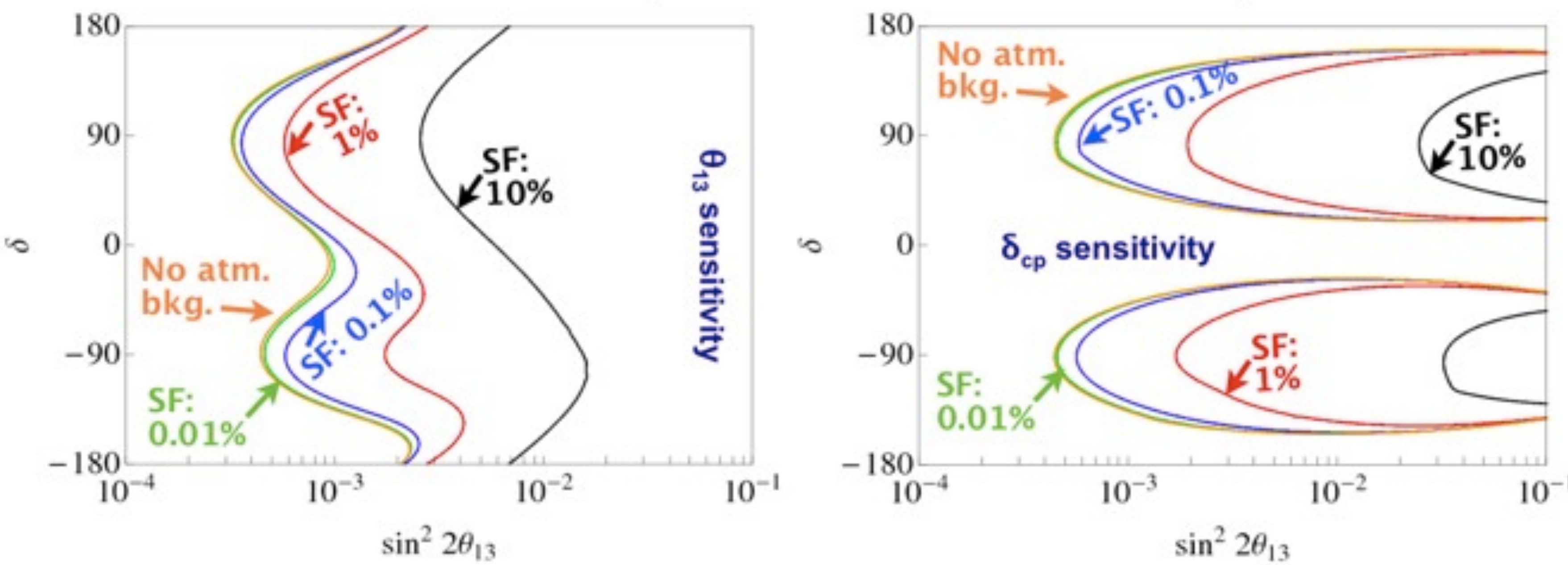


DR: Injection Scheme

- After "merging" the bunches are ~ 2m long (all ions)
- 20 bunches from SPS to DR
  → **SF = 20 · 2m / 6911m = 0.58%**
- I.e. between 0.1% and 1%
- With the intensities shown in previous slide we get these sensitivities:



Assumed Fluxes: 1.1e18 ν/year from ^{18}Ne and 2.9e18 anti-ν/year from ^6He



- **<u>Good, BUT:</u>**
  - ➡ **What about collective effects?**

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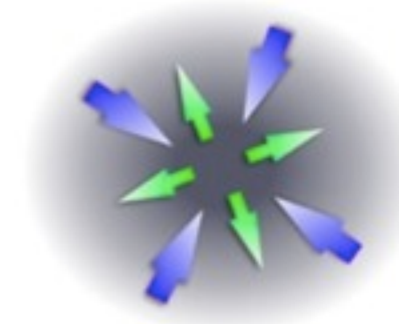
BB Collective Effects

COLLECTIVE

- High intensity ion beams are foreseen for the Beta Beam project
- High intensity bunches can have non-negligible amount of charges
  - ➡ Particles interact with each other and vacuum chamber
    - ✦ "Collective Effects"
- Collective Effects limit the final performance of accelerators
- The studies of instabilities of the ion beams are a crucial part of the Beta Beam project
- Studies will be done for all ions (FP6: ^{18}Ne & ^{6}He, FP7: ^{8}B & ^{8}Li) and for all machines (so far only DR)

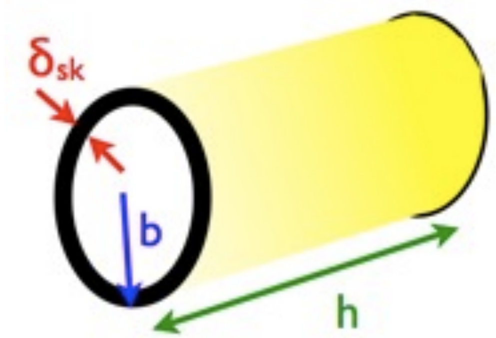
COLLECTIVE

Reasons for Instabilities

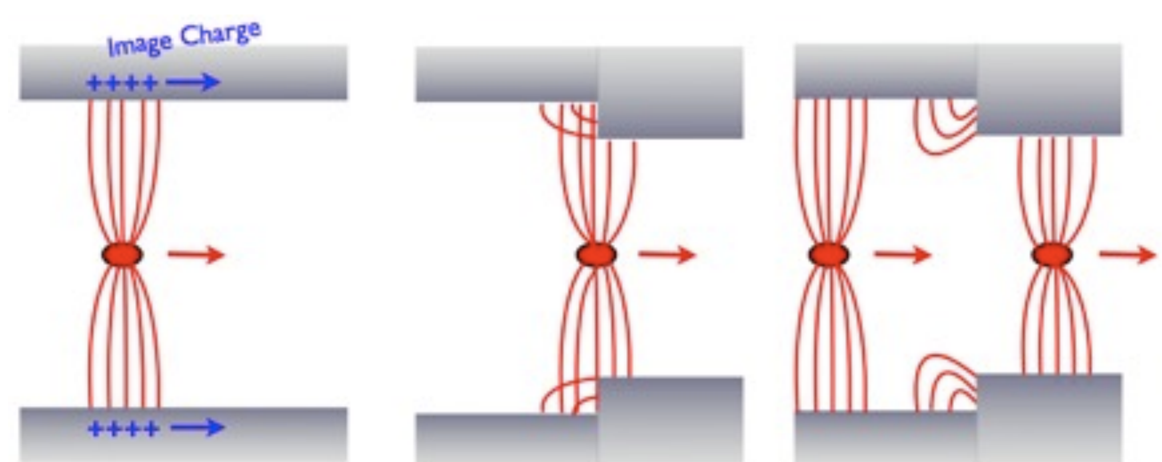


- Different reasons for Instabilities:
    - ➡ Coulomb Forces
        - within the bunch; "**Direct Space Charge**"
        - between bunch and pipe; "**Image Field**"

    } "Laslett's Tune Shifts"



- ➡ Wake Fields *(= "Impedances" in frequency domain)*
    - due to resistive pipe; "**Resistive Wall Impedance**"
    - due to pipe discontinuities; "**Resonance Impedance**"



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Laslett's Tune Shifts

LASLETT'S

- **Direct Space Charge** forces are repulsive and proportional to distance from center → to be compared to quadrupoles → betatron tune shift
  - ➡ but $\Delta Q_{DSC_{x,y}} \propto \frac{1}{\gamma^2}$ since for relativistic beams the repulsive **E forces** are cancelled by the contracting **B forces**

  - ➡ For DR (γ=100) $|\Delta Q_{DSC}| < 0.2$ ☺

$|\Delta Q_{DSC}| > 0.2$ could cause tune crossings over resonance lines → instabilities

SC	DR ^{18}Ne	DR ^{6}He
ΔQ_{dsc_x}	-0.0409	-0.0083
ΔQ_{dsc_y}	-0.0946	-0.0192
ΔQ_x^{incoh}	-0.0409	-0.0083
ΔQ_y^{incoh}	-0.0946	-0.0192
$\Delta Q_x^{coh\,p}$	-1.7470e-04	-3.5564e-05
$\Delta Q_y^{coh\,p}$	-3.1937e-04	-6.5016e-05
$\Delta Q_x^{coh\,np}$	-6.2768e-05	-1.2765e-05
$\Delta Q_y^{coh\,np}$	-1.1475e-04	-2.3337e-05

- For PS with low γ ΔQ_{DSC} could be crucial (to be investigated)

- **Image Fields** turned out to have even less effects in the DR

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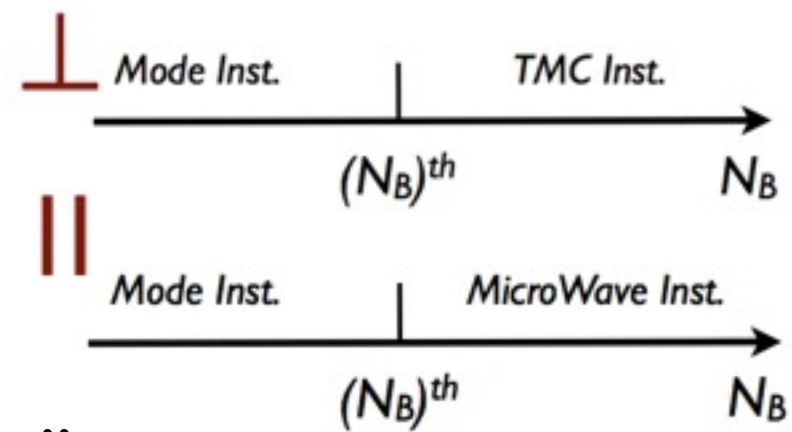
Wake Field Instabilities

WAKE FIELDS

- Wake Fields are described by
  - ➡ Wake Potential; $W(t)$, in time domain
  - ➡ Impedance; $Z(\omega)=\mathcal{F}[W(t)]$, in frequency domain
- Instabilities caused by $Z(\omega)$ are described by different theories depending on the intensity regime



  - If $N_b < N_b^{th}$ instabilities are "modest"
  - If $N_b > N_b^{th}$ instabilities will cause beam loss
  - ➡ Important to find N_b^{th} since that is absolute maximum number ions we can have per bunch
- N_b^{th} will have to be found for each type of $Z(\omega)$;
  - Resistive Wall and Resonance Impedance
  - Longitudinal and Transversal Impedance

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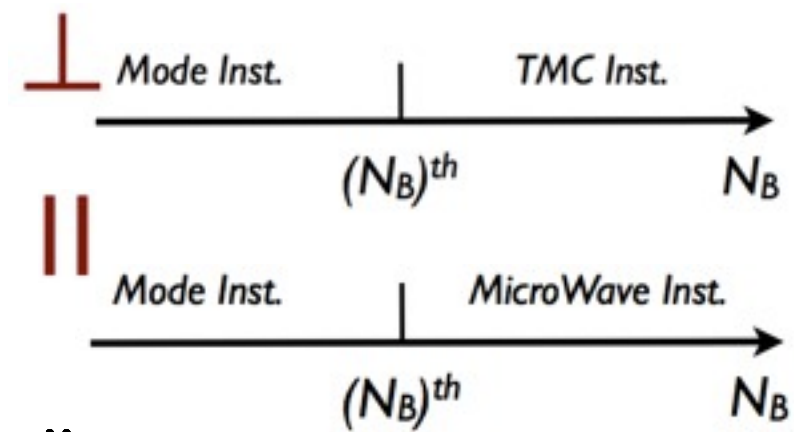

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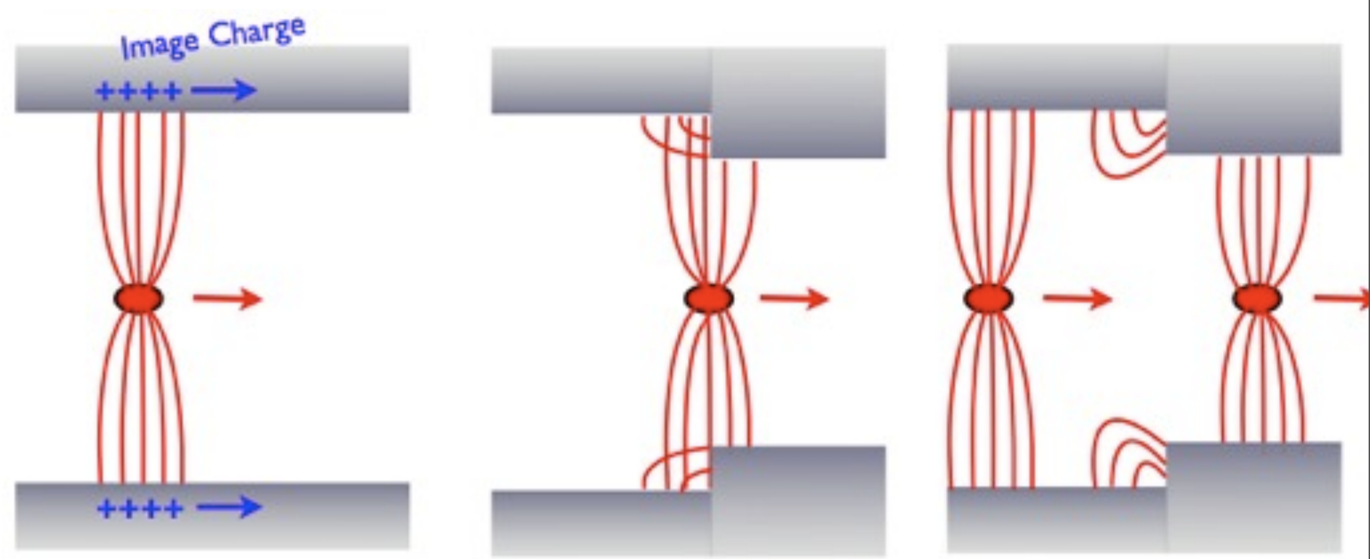
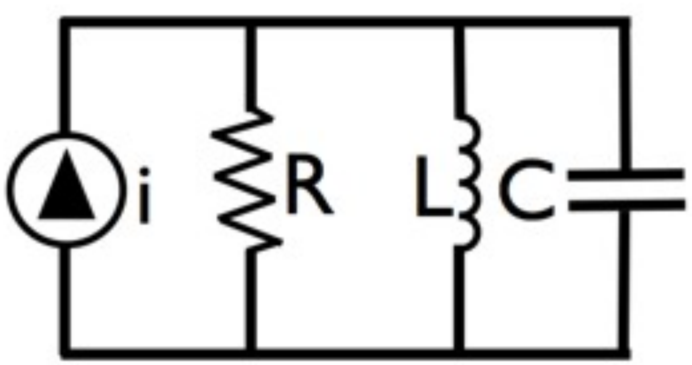
DR
^{18}Ne & ^{6}He

Resonance Impedance

WAKE FIELDS

- Wake fields can be trapped in e.g. cavities in the beam pipe → Resonance Impedance → Can be modeled with an RLC circuit:

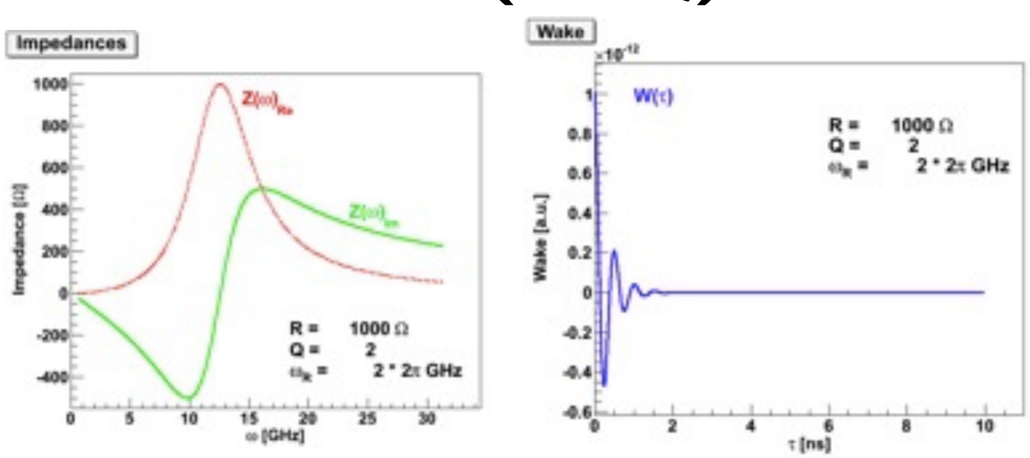




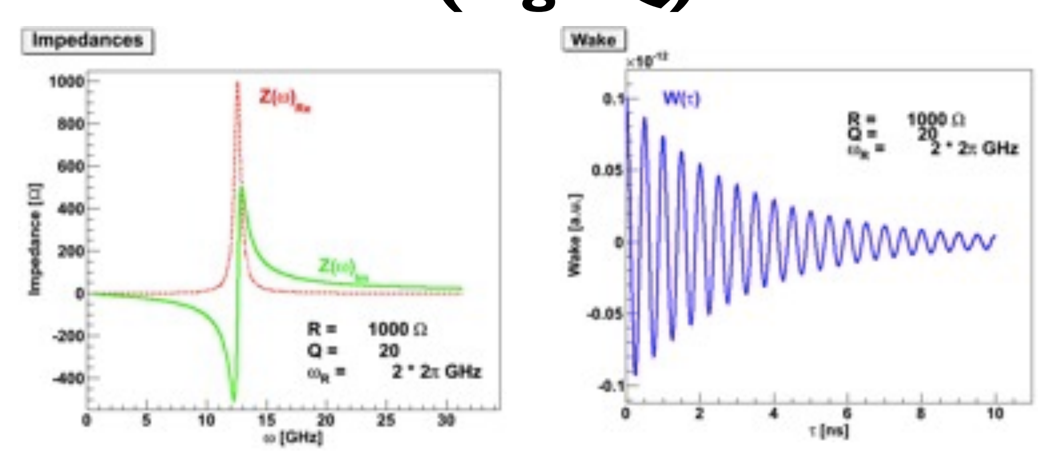
$$Z_\perp(\omega) = \frac{R_\perp \frac{\omega_r}{\omega}}{1 + iQ\left(\frac{\omega_r}{\omega} - \frac{\omega}{\omega_r}\right)}$$

Q = Quality Factor, $R_\perp$ = Shunt Impedance, ω_r = Resonance Angular Frequency

Broad Band (low Q)



Narrow Band (high Q)



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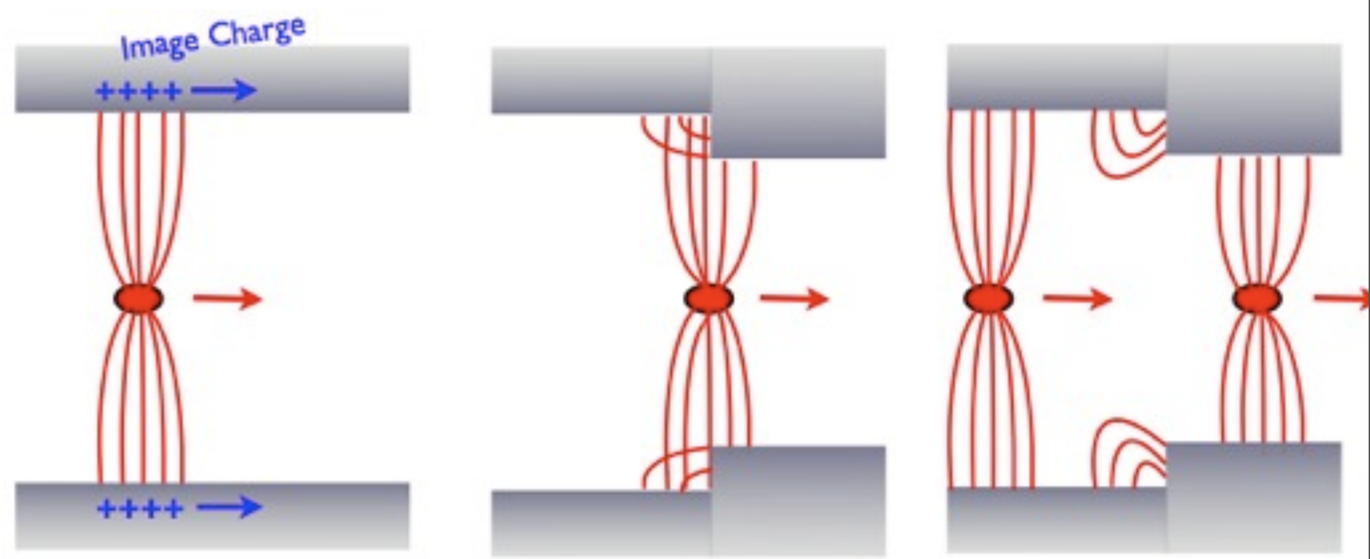

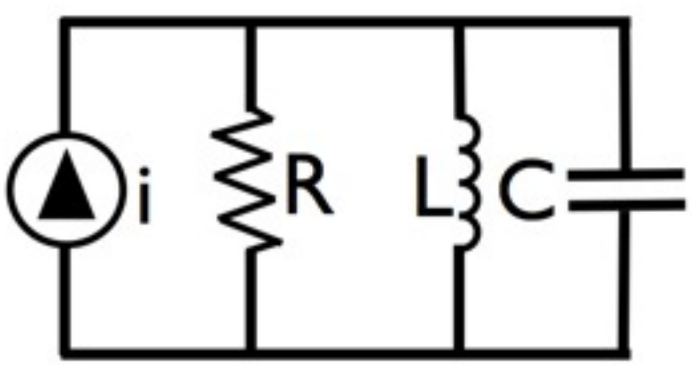

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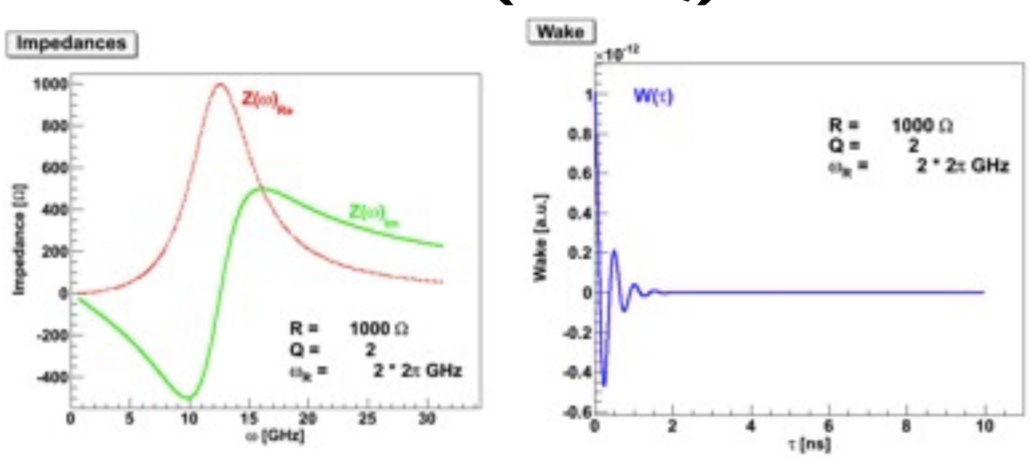

Will only show results for

- ^{18}Ne & ^{6}He in Decay Ring
- Transversal
- Resonance
- Broad Band (Q=1)

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DR Intensity Threshold

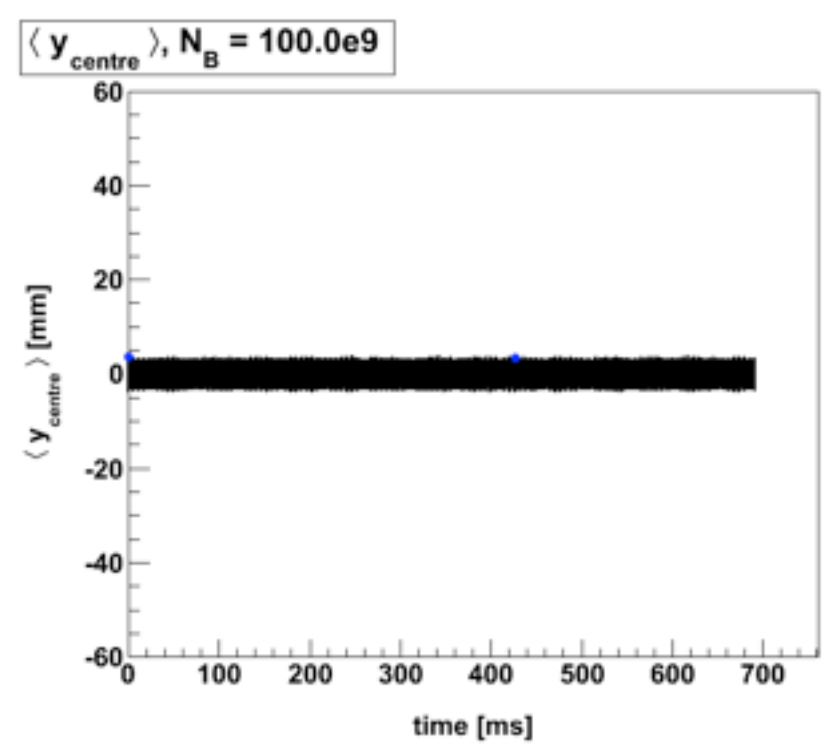
HEADTAIL / MOSES

E. Métral, CERN, Overview of Single-Beam Coherent Instabilities in Circular Accelerators

- Three different ways to find N_b^{th}:
  - ➡ A theoretical equation, "Coasting Beam Eq.":

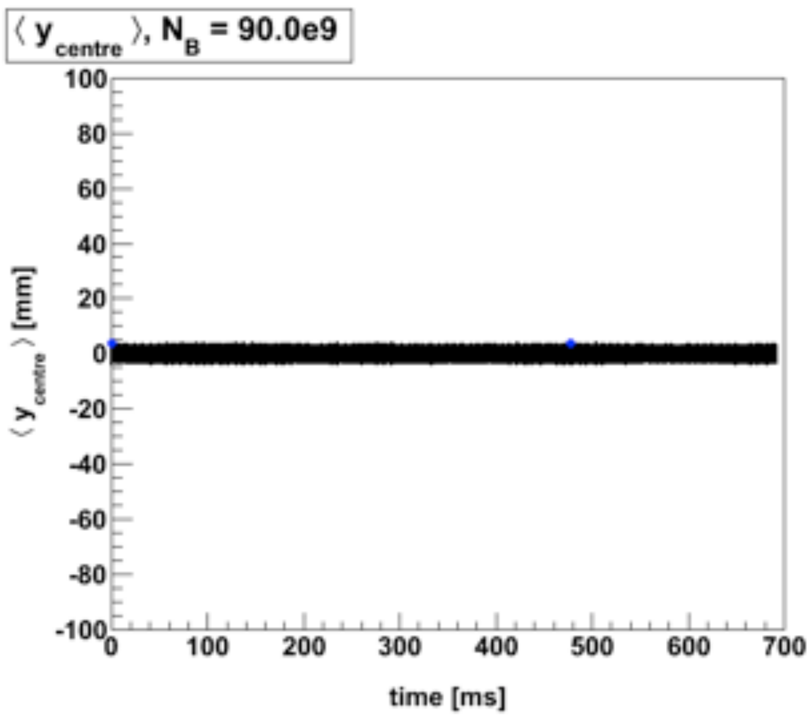
$$N_{b_{x,y}}^{th} = \frac{32}{3\sqrt{2}\pi} \frac{Q_{x,y}|\eta|\varepsilon_l^{2\sigma}\,\omega_r}{Z^2\beta^2 c} \left(\Re\left[Z_{\perp_{x,y}}^{BB}\right]_{max} \right)^{-1} \left(1 + \frac{\omega_{\xi_{x,y}}}{\omega_r}\right)$$

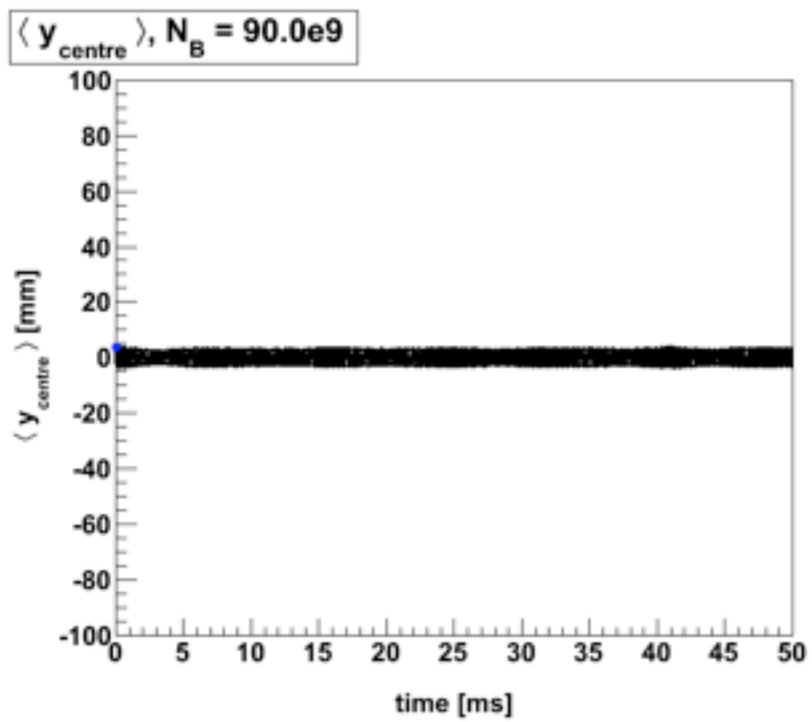
  - ➡ A program calculating the theoretical instability rise time depending on the intensity, "MOSES"
  - ➡ A multi-particle tracking simulation, "HEADTAIL"
    - ✦ One of HEADTAIL's output, the vertical mean beam center, is shown here for different bunch intensities
    - ✦ Exponential least square fit is used to get the Growth Rate, 1/τ

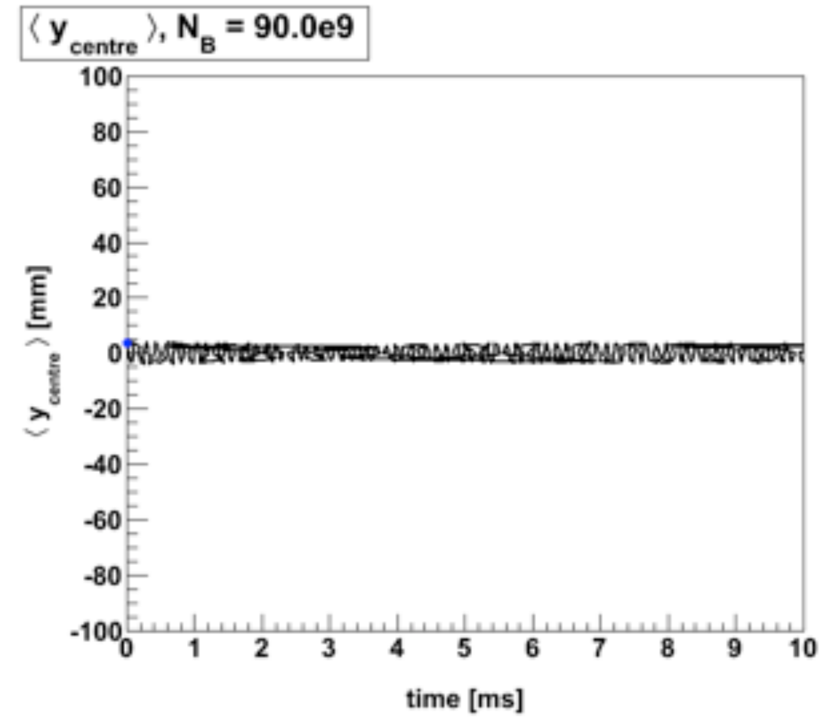


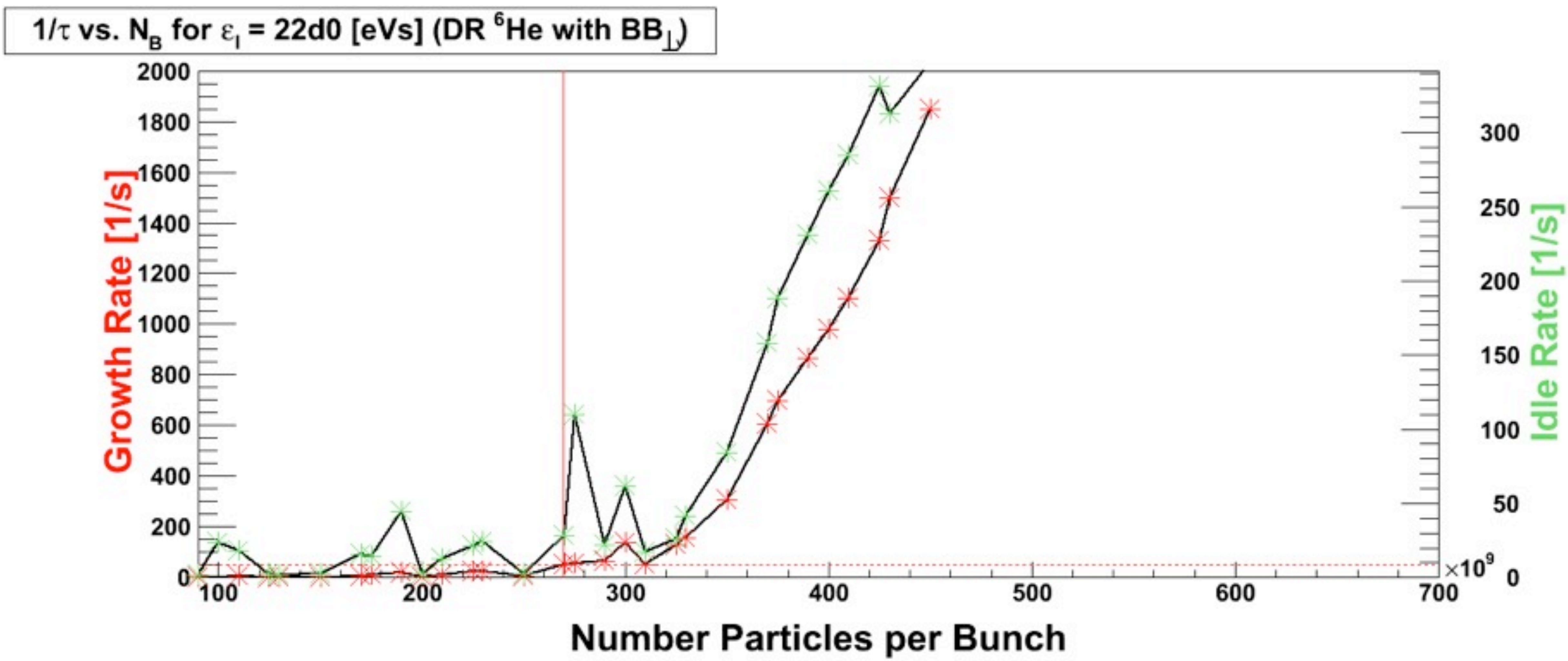
Growth Rate from HEADTAIL

HEADTAIL / MOSES



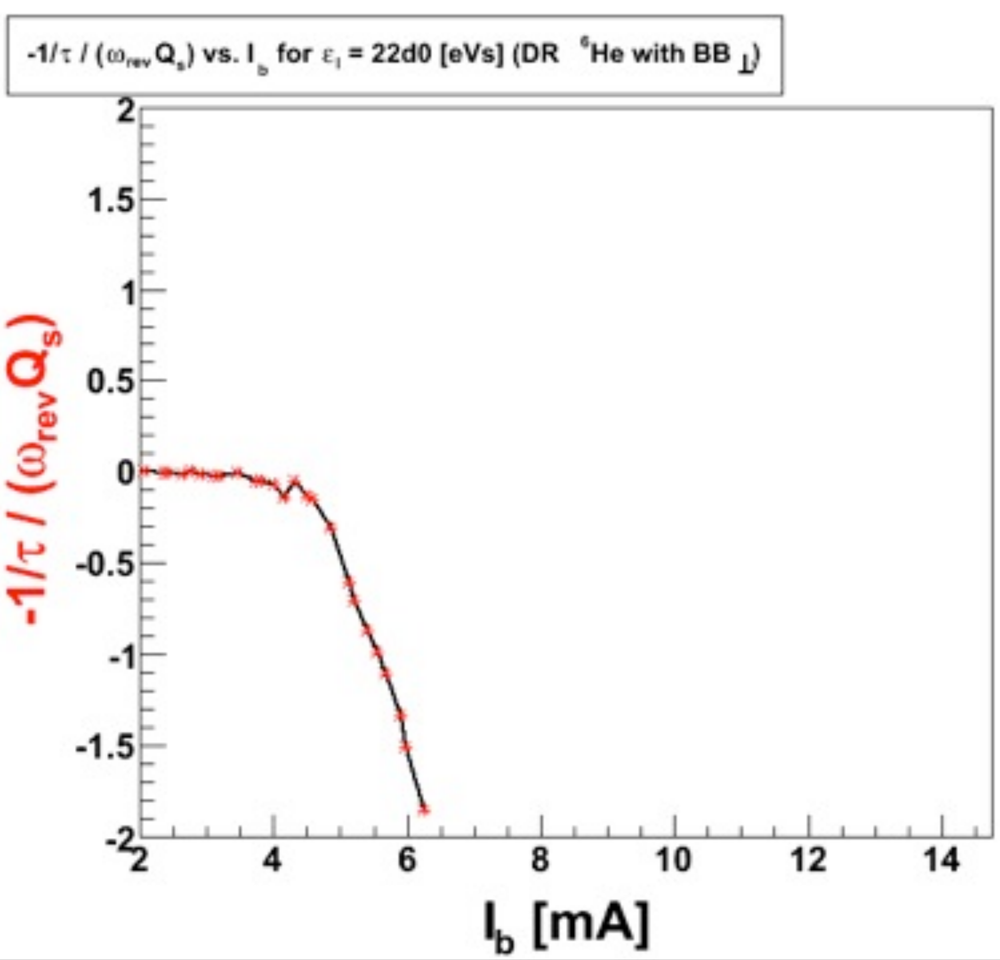


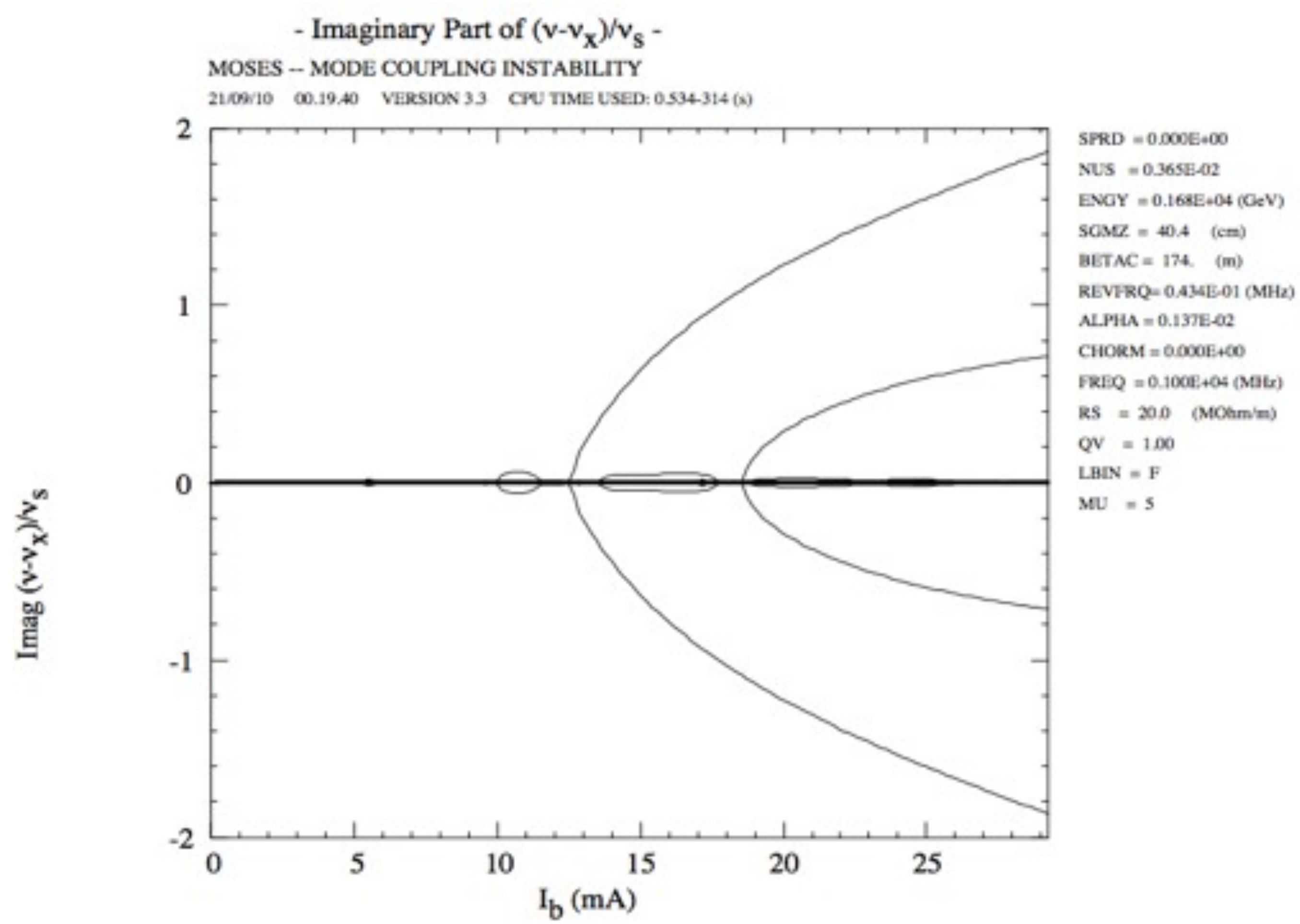




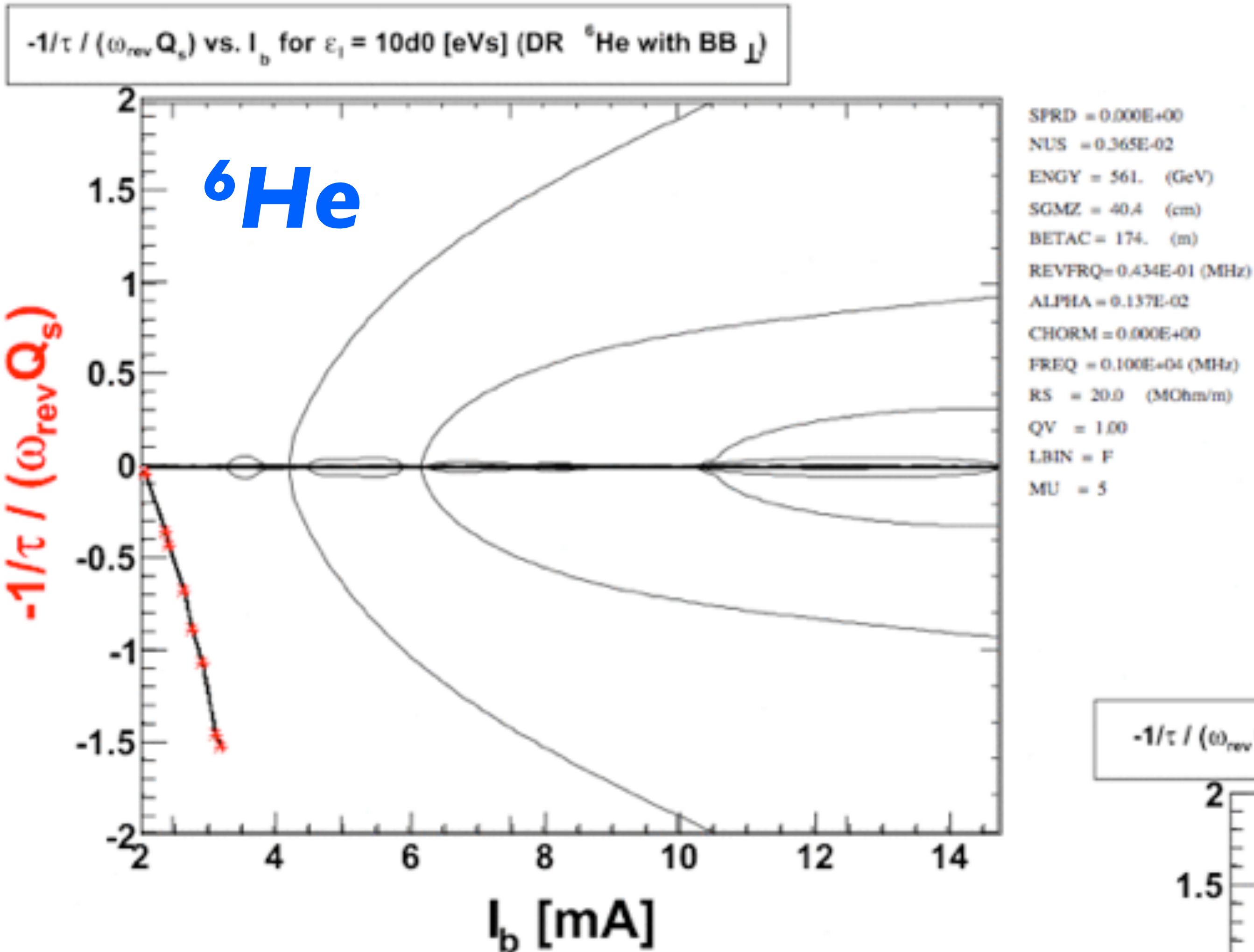
MOSES' Scales

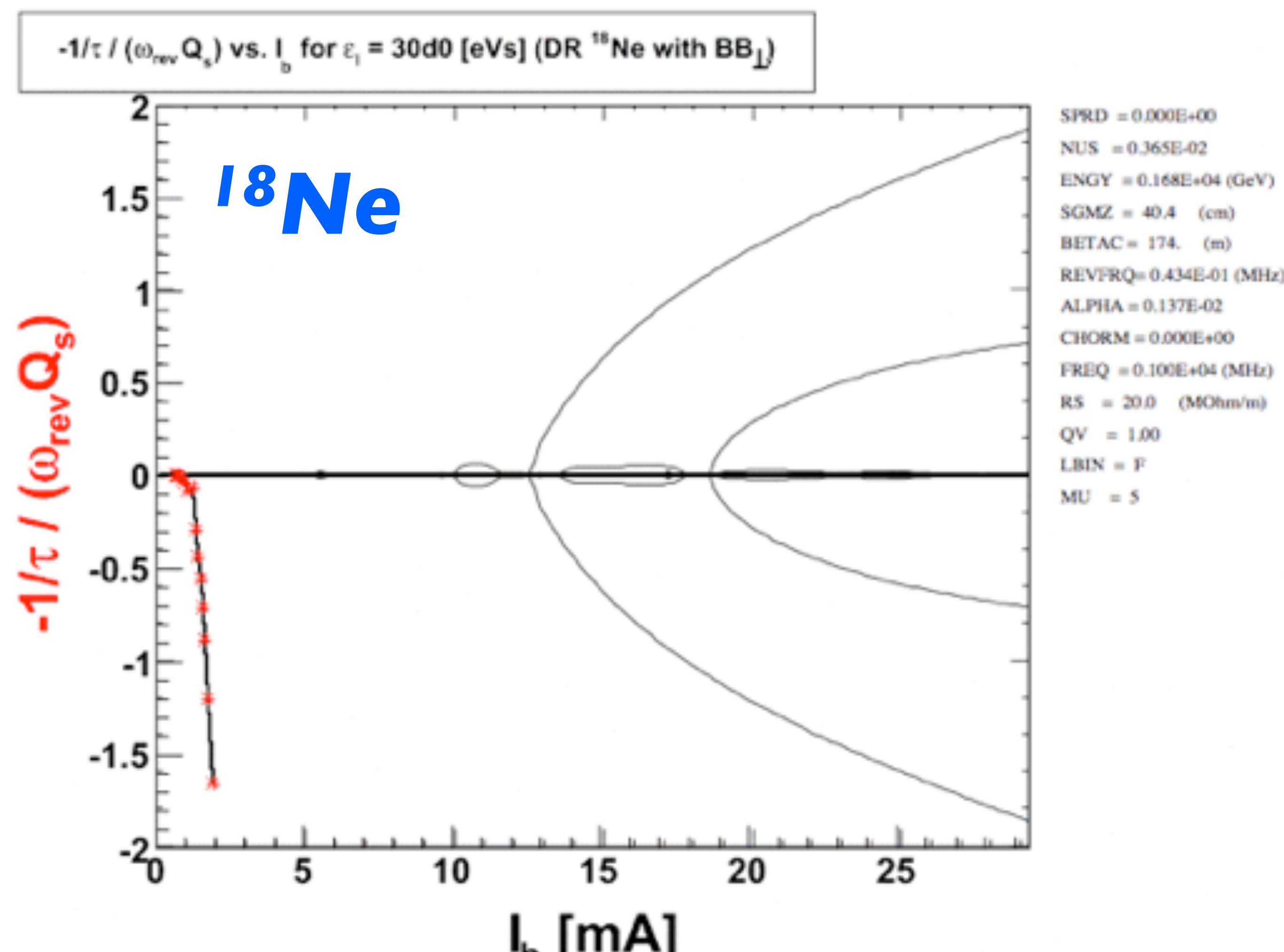
- **To get same scale as MOSES' plots:**
- **X-axis:** $\frac{1}{\tau} \rightarrow \frac{\Im[\Delta Q]}{Q_s} = -\frac{1/\tau}{\omega_{rev} Q_s}$ **since** $1/\tau = -\Im[\Delta Q]\,\omega_{rev}$
- **Y-axis:** $N_B \rightarrow \frac{ZeN_B}{T_{rev}} = I_b$





Emittance Scan - No Z Correction





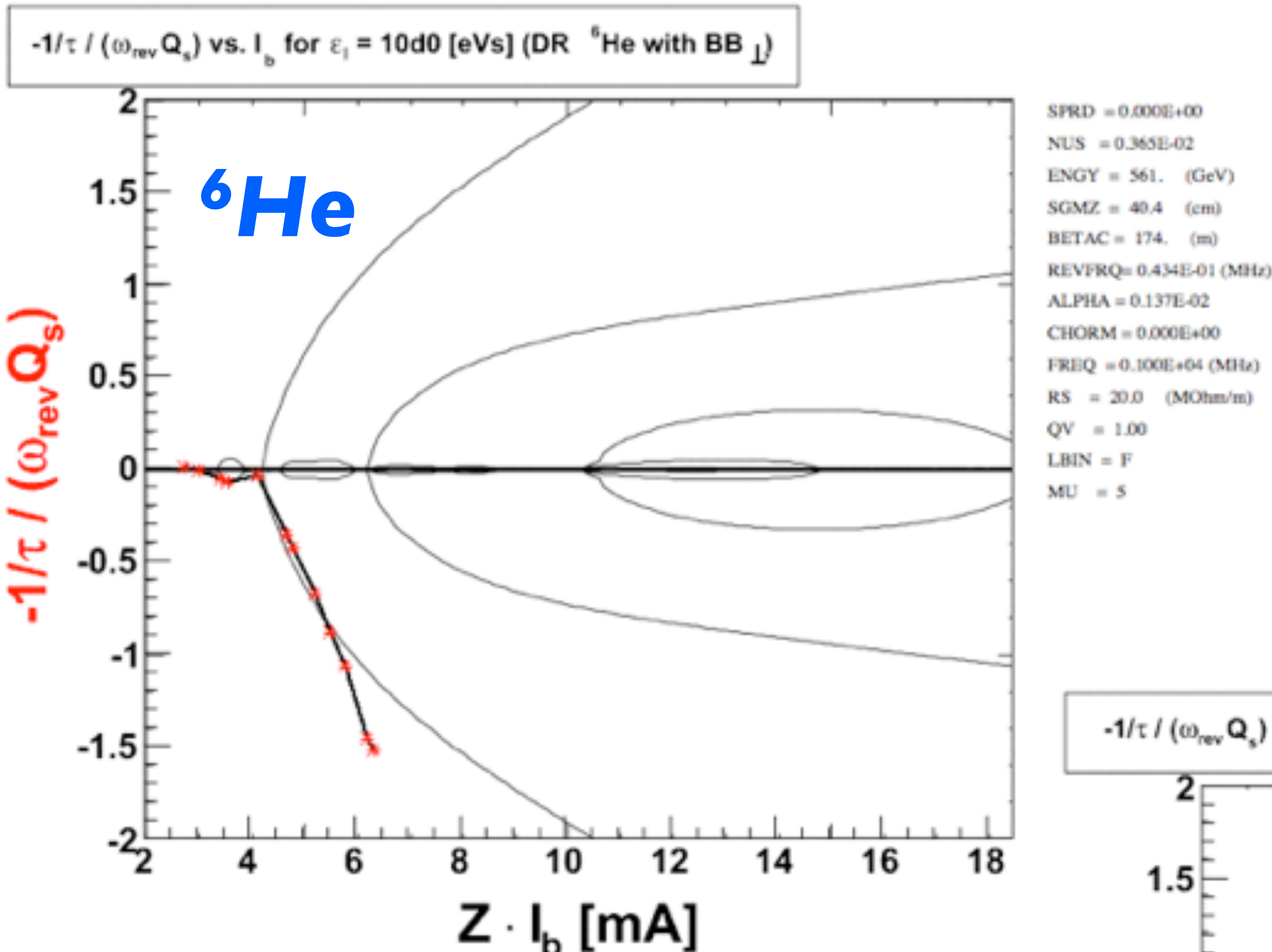
Z Correction

- To get the ion equivalent results from MOSES
  - ➡ Let's assume for simplicity MOSES solves Sacherer's equation for protons, then we see

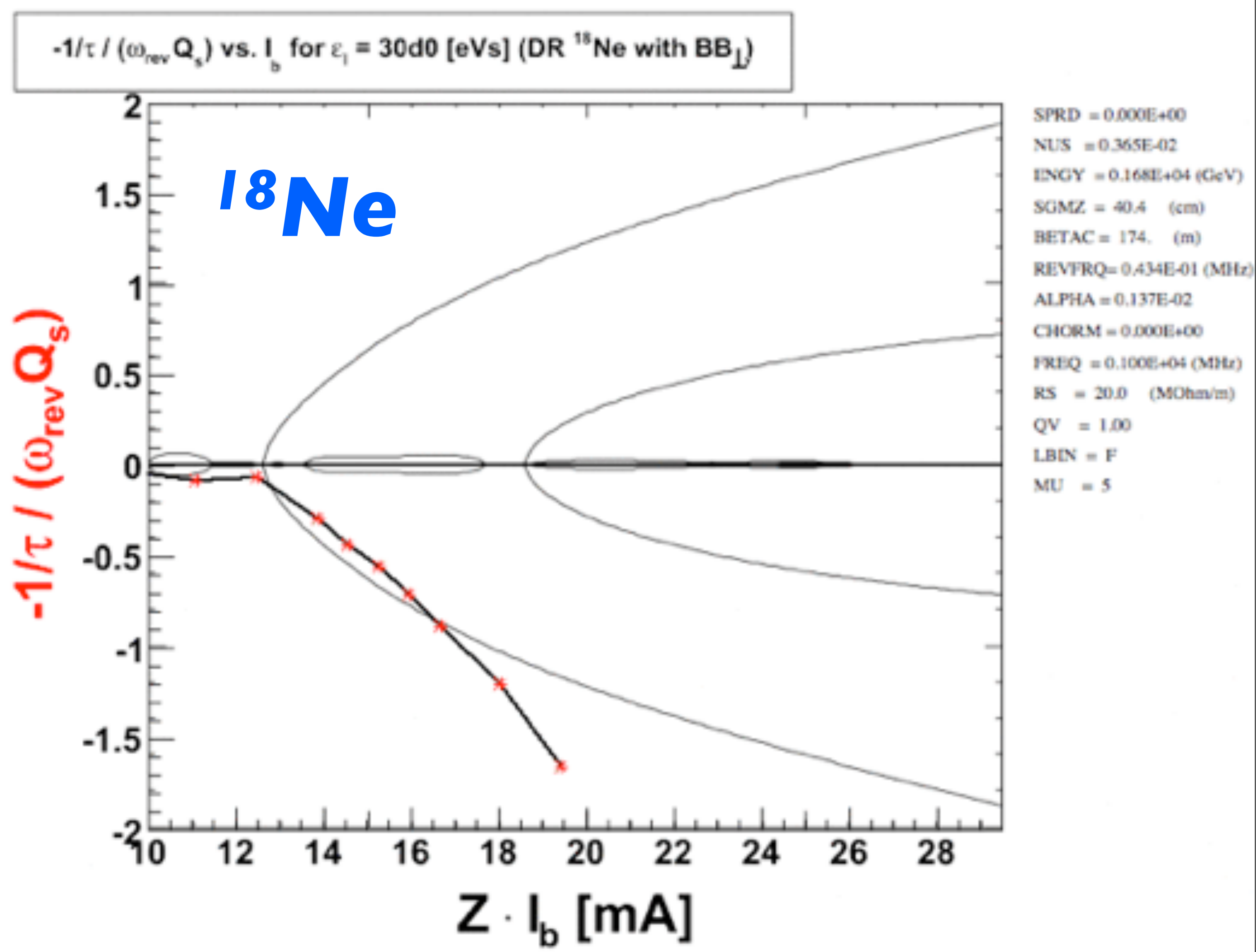
$$\left(\frac{1}{\tau}\right)^{m,n}_{\perp_{x,y}} = \frac{-1}{|n|+1} \frac{ZeI_bC\langle\beta_{x,y}\rangle\omega_{rev}}{4\pi E_{tot}L_b} \frac{\sum_{p=-\infty}^{\infty} \Re\left[Z_\perp(\omega_p)\right] h_{|n|}(\omega_p - \omega_\xi)}{\sum_{p=-\infty}^{\infty} h_{|n|}(\omega_p - \omega_\xi)}$$

  - ➡ that the current, I_b, should be multiplied by the charge number, Z, to get the correct growth rate
  - ➡ We also see that the mass number, A, is included in the total energy, E_{tot}
  - ➡ So the correction is: Multiply x-axis with Z

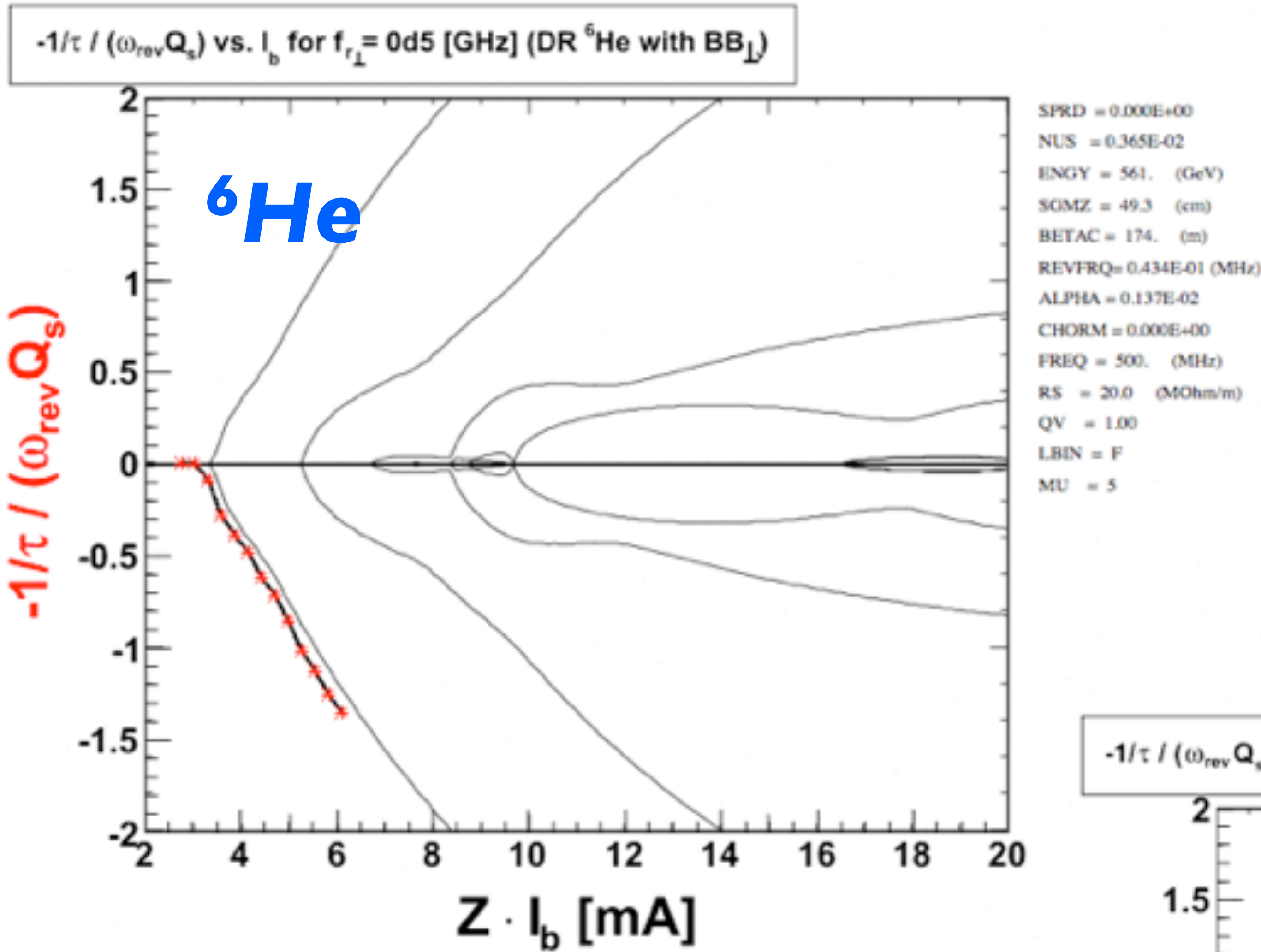
Emittance Scan - Z Correction



- **Z Correction seems to work perfect only for big growth rate**
  - ➡ **Any other idea... ?**



Res. Freq. Scan - Z Correction



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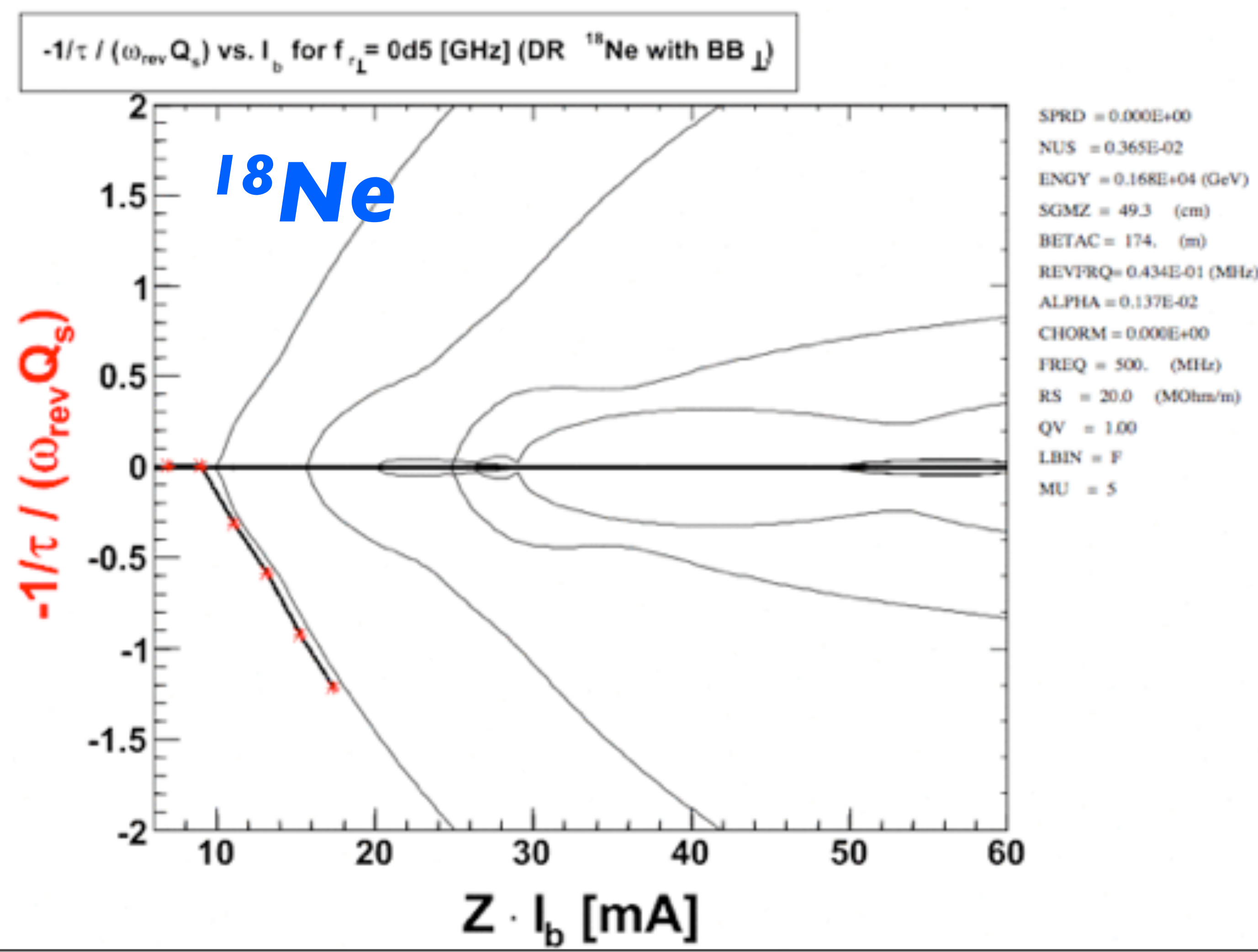

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  - ➡ Laslett's Tune Shifts
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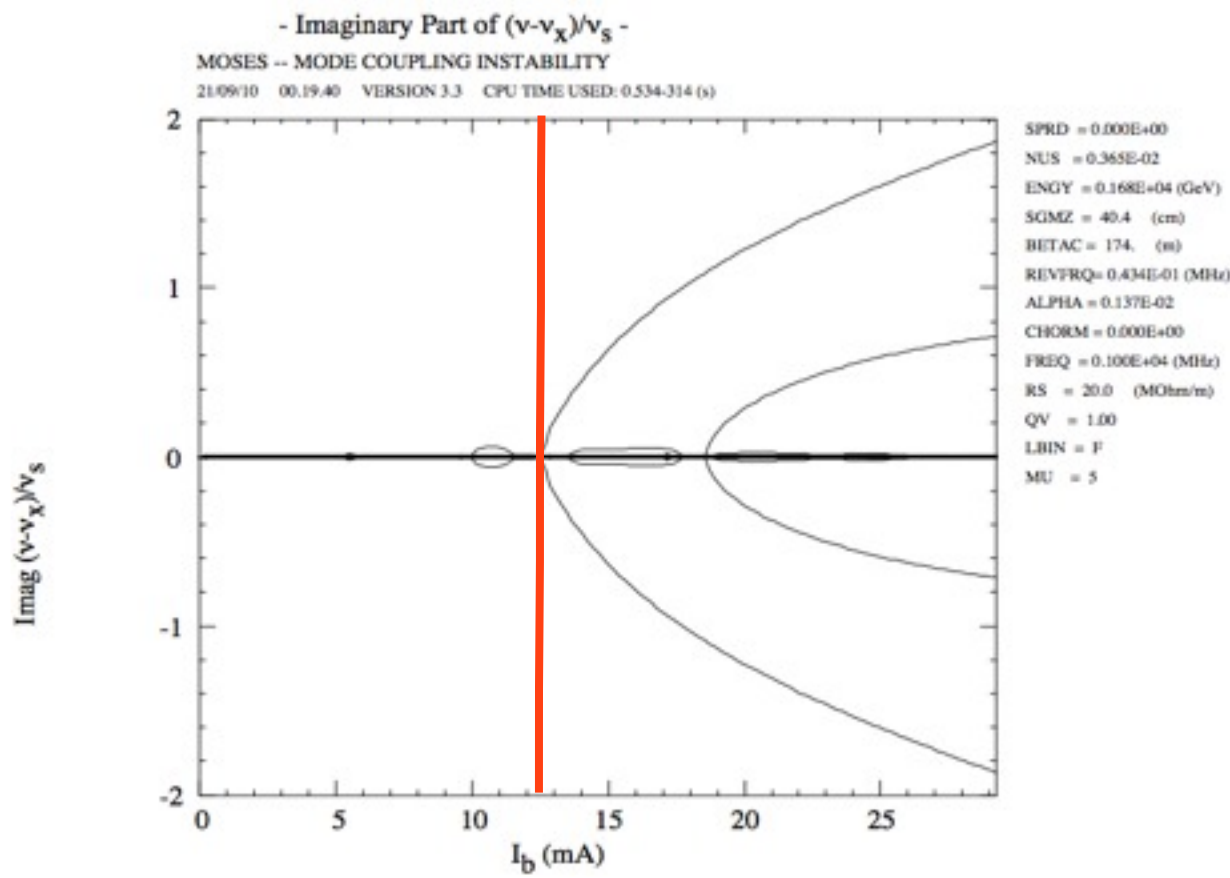
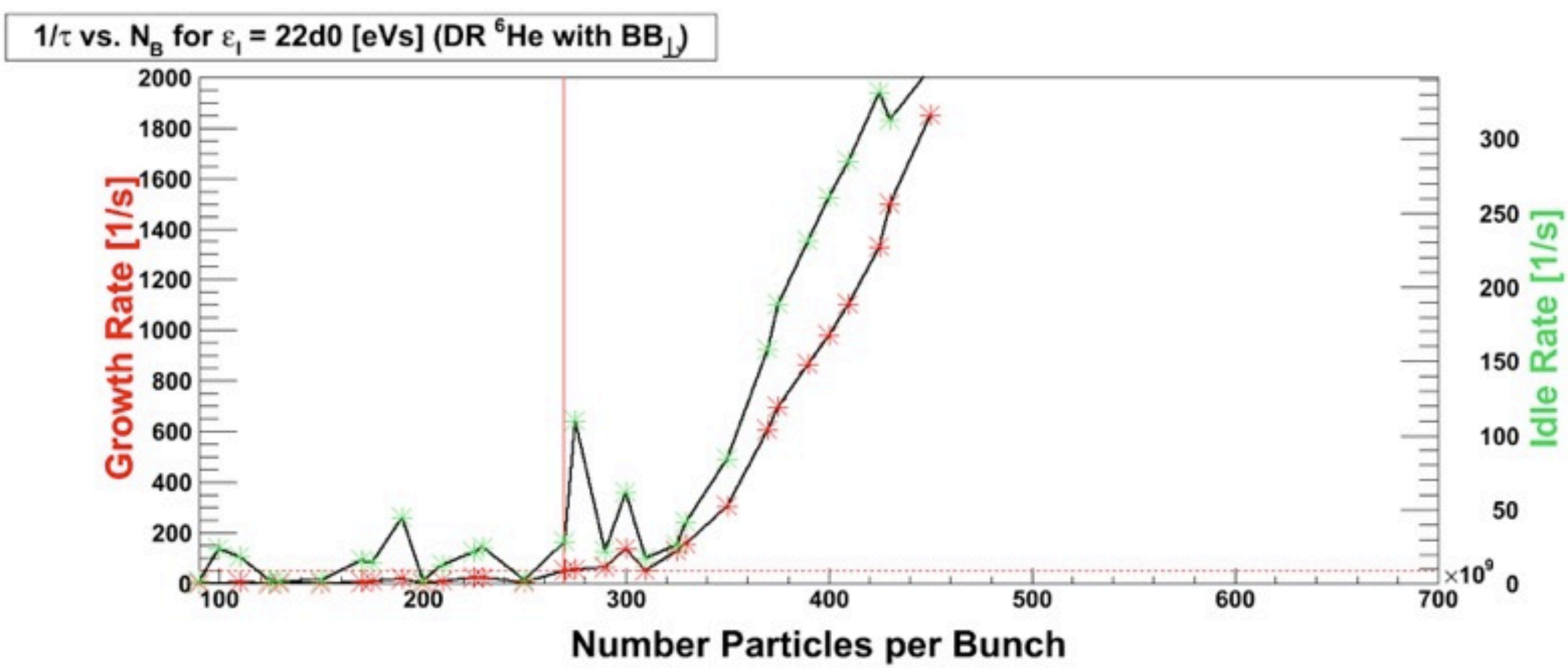
Intensity Threshold

THRESHOLD



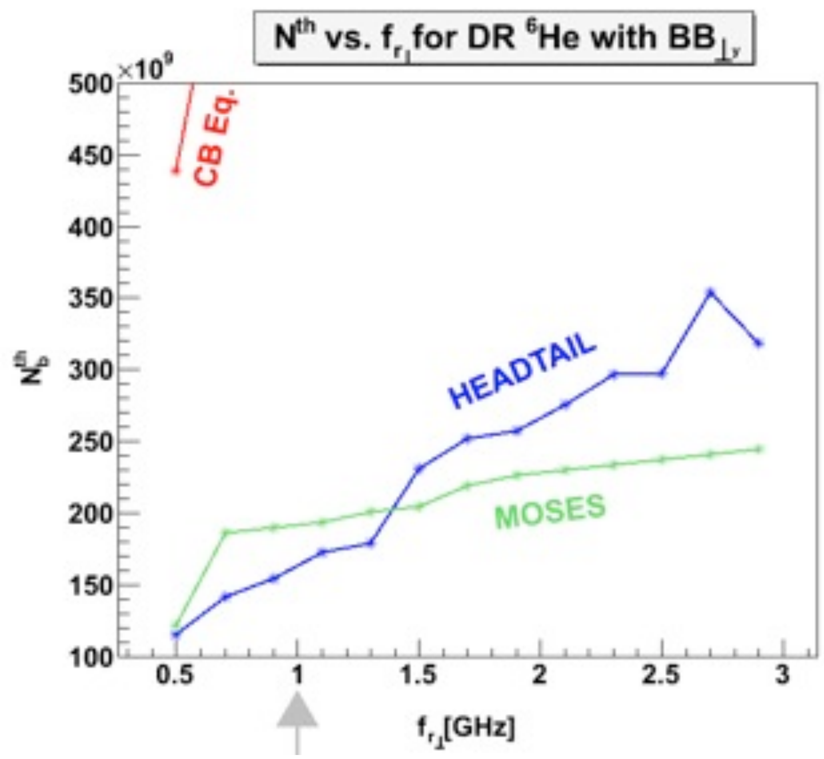
- MOSES: Get the ion equivalent threshold $\mathbb{I}_b{}^{th} = I_b{}^{th} / Z$ and then $N_b{}^{th} = T_{rev}\, \mathbb{I}_b{}^{th} / Ze$
- HEADTAIL: Define threshold growth rate $(1/\tau)^{th} = 50$ Hz



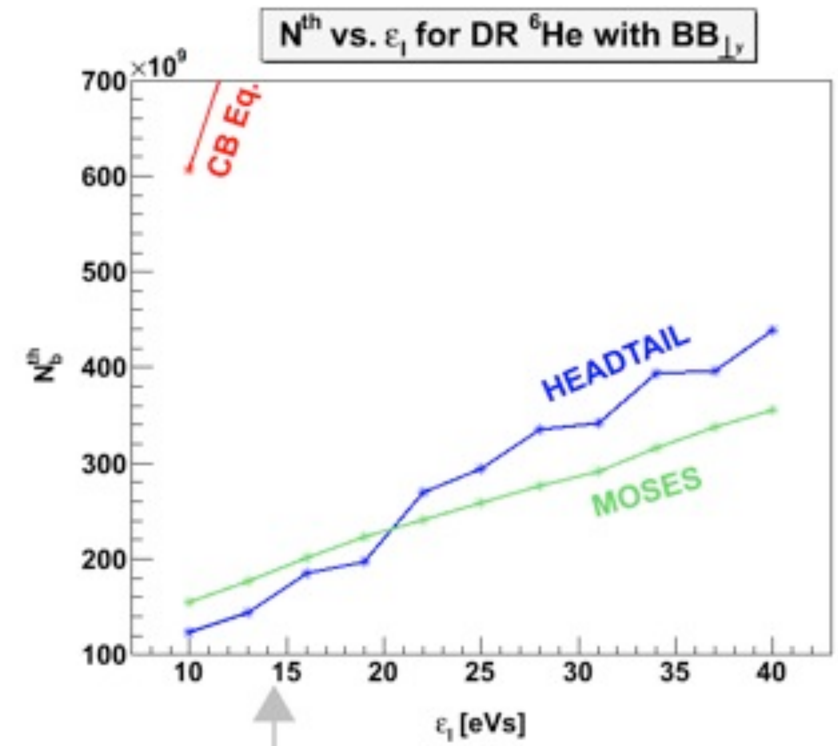
Scans for ^{6}He in DR

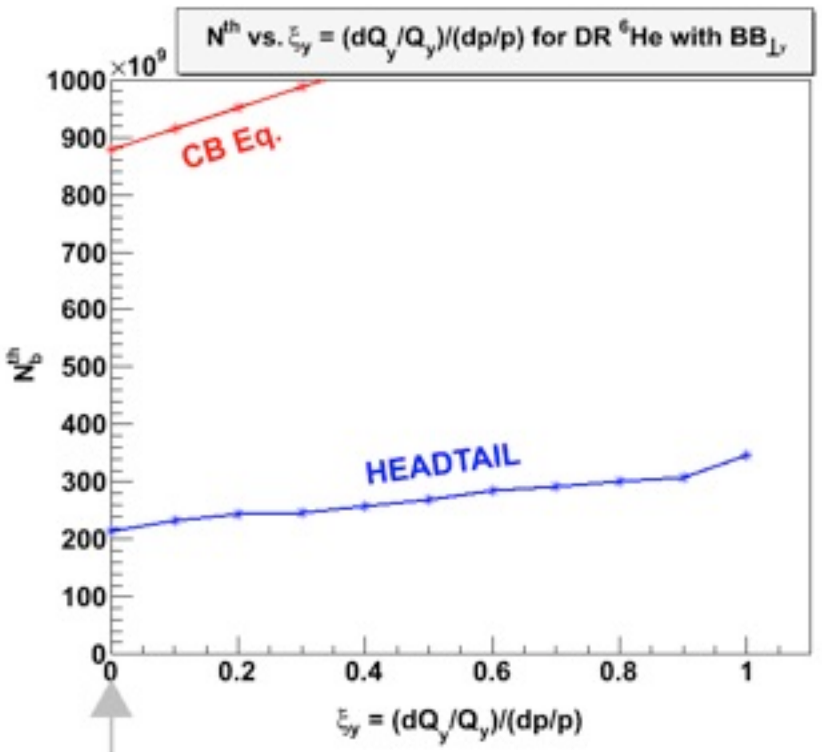
THRESHOLD

- **Scan over Resonance Frequency** →



- **Scan over Longitudinal Emittance** →



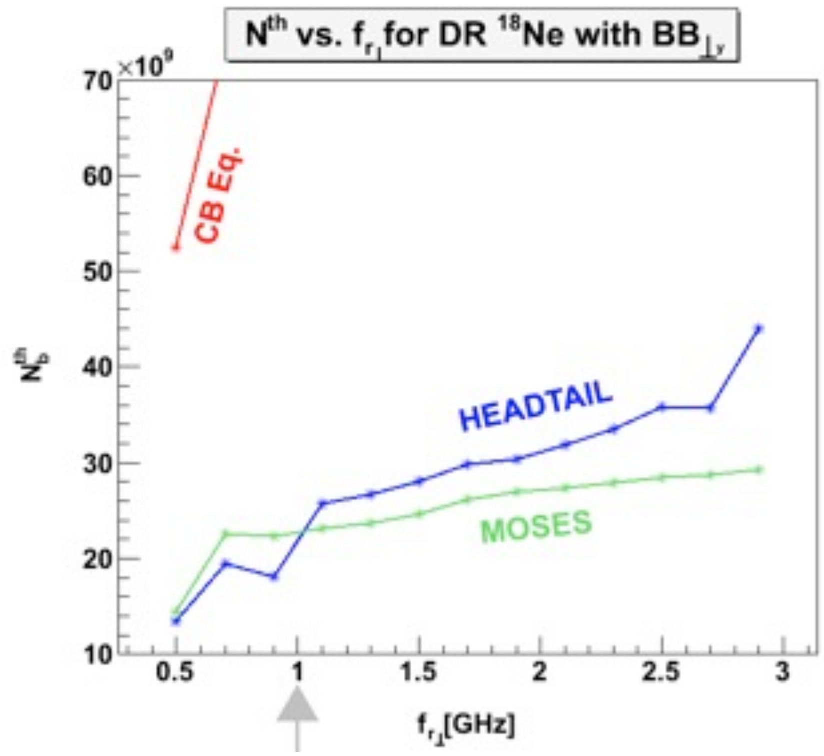


- **Scan over Chromaticity with $(1/\tau)^{th}$ = 100 Hz** ←

Scans for ^{18}Ne in DR

THRESHOLD

- **Scan over Resonance Frequency** →



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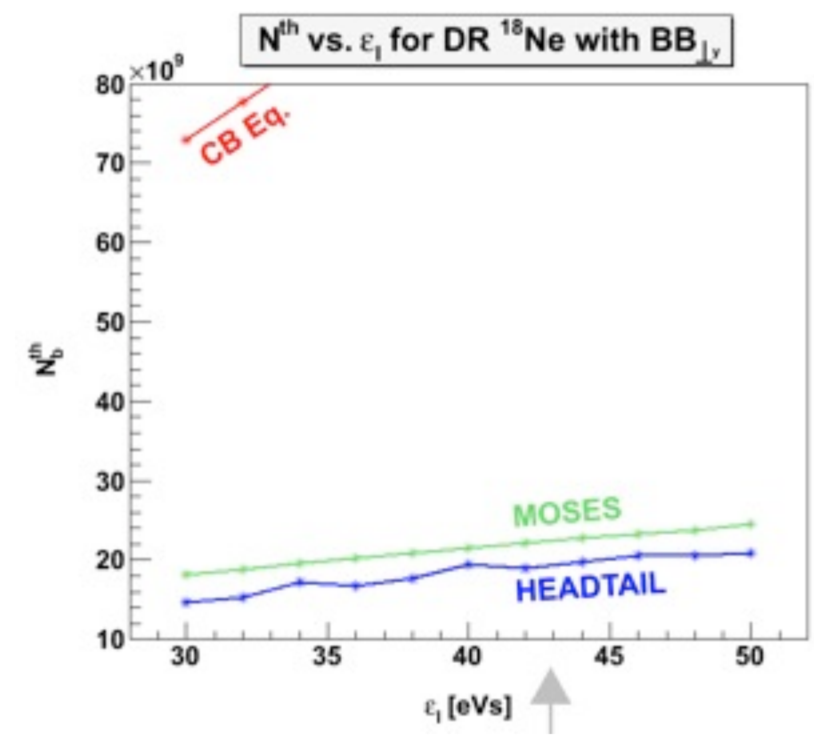

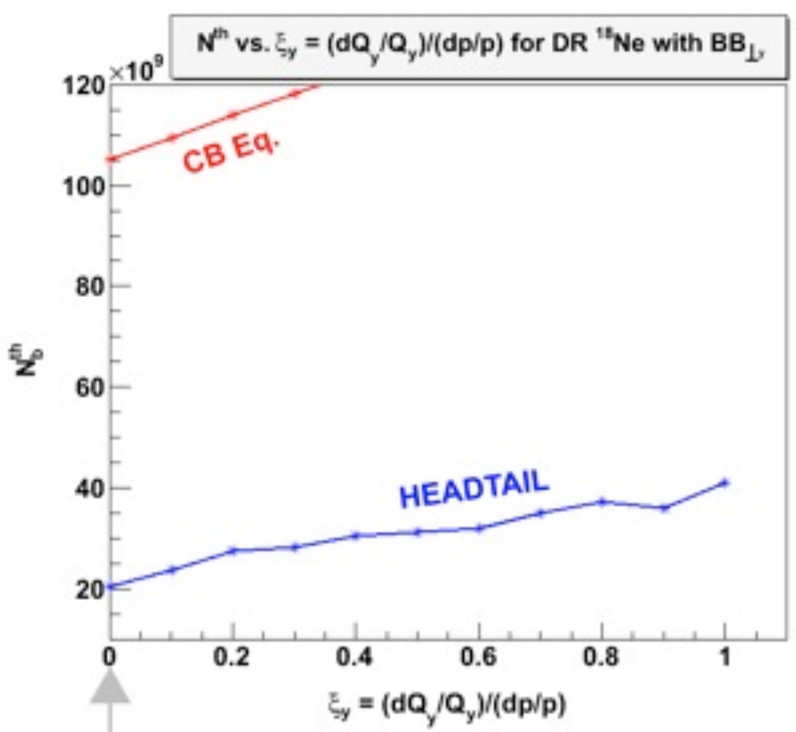

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N_b^{th} vs. $R_\perp$ in DR

THRESHOLD

- **None of the parameters we scanned over so far, ε_l, f_r and ξ, seem to manage to improve N_B^{th} up to the level we want:**

$$N_B^{^6He} = 4.0 \cdot 10^{12} \qquad N_B^{^{18}Ne} = 3.1 \cdot 10^{12}$$

- **Let's see how much smaller $R_\perp$ have to be compared to $R_\perp^{sps}$ = 20 MΩ/m to allow N_B^{th}**

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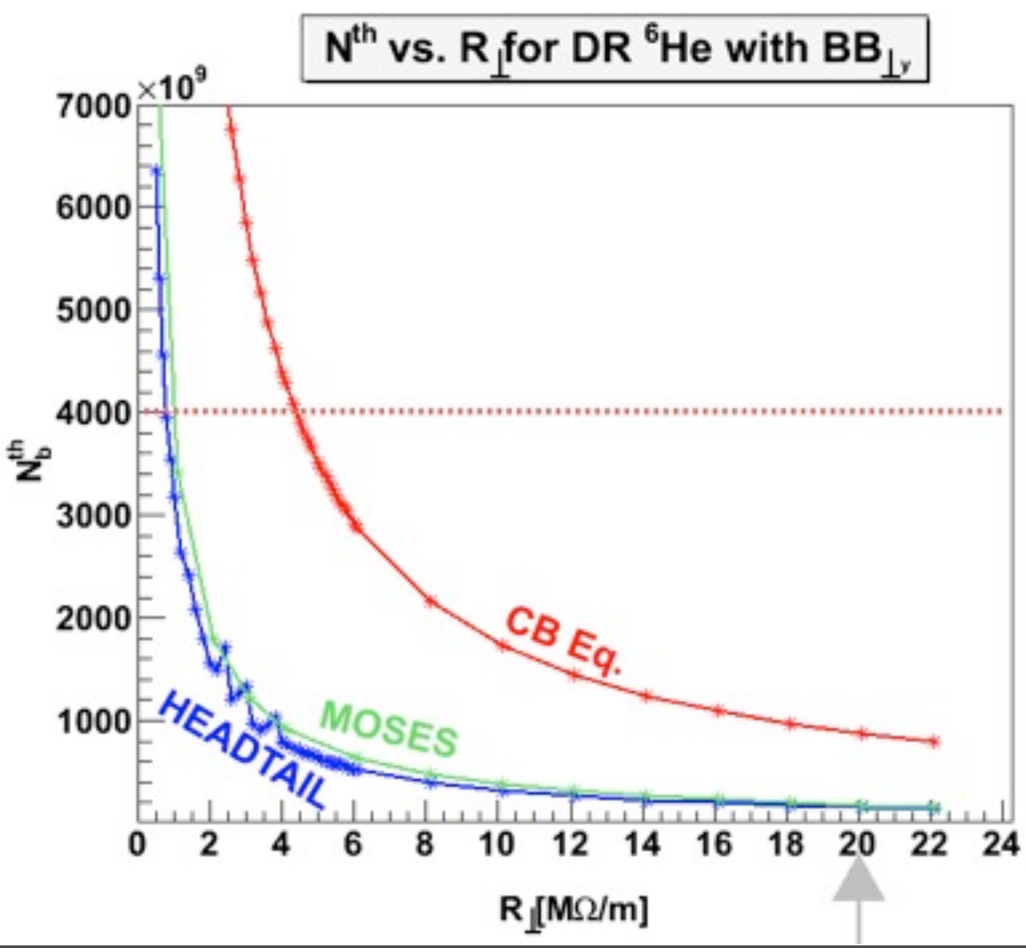

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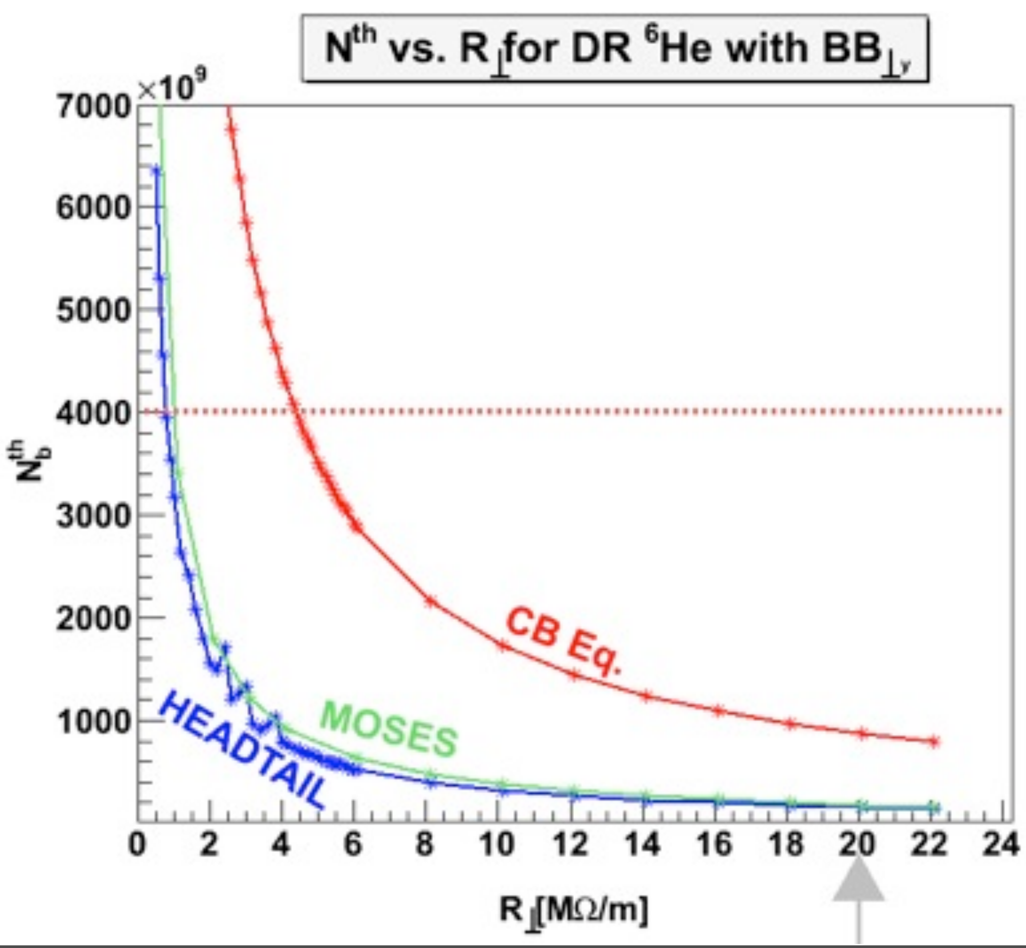

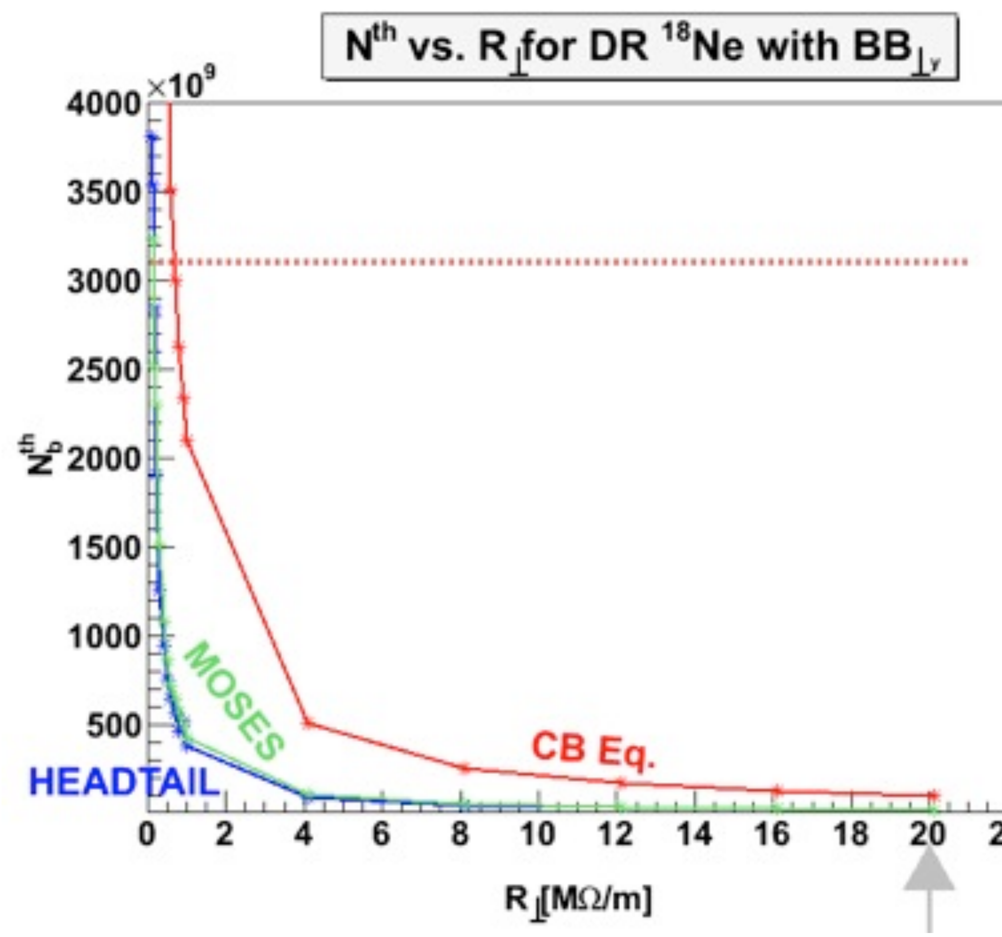

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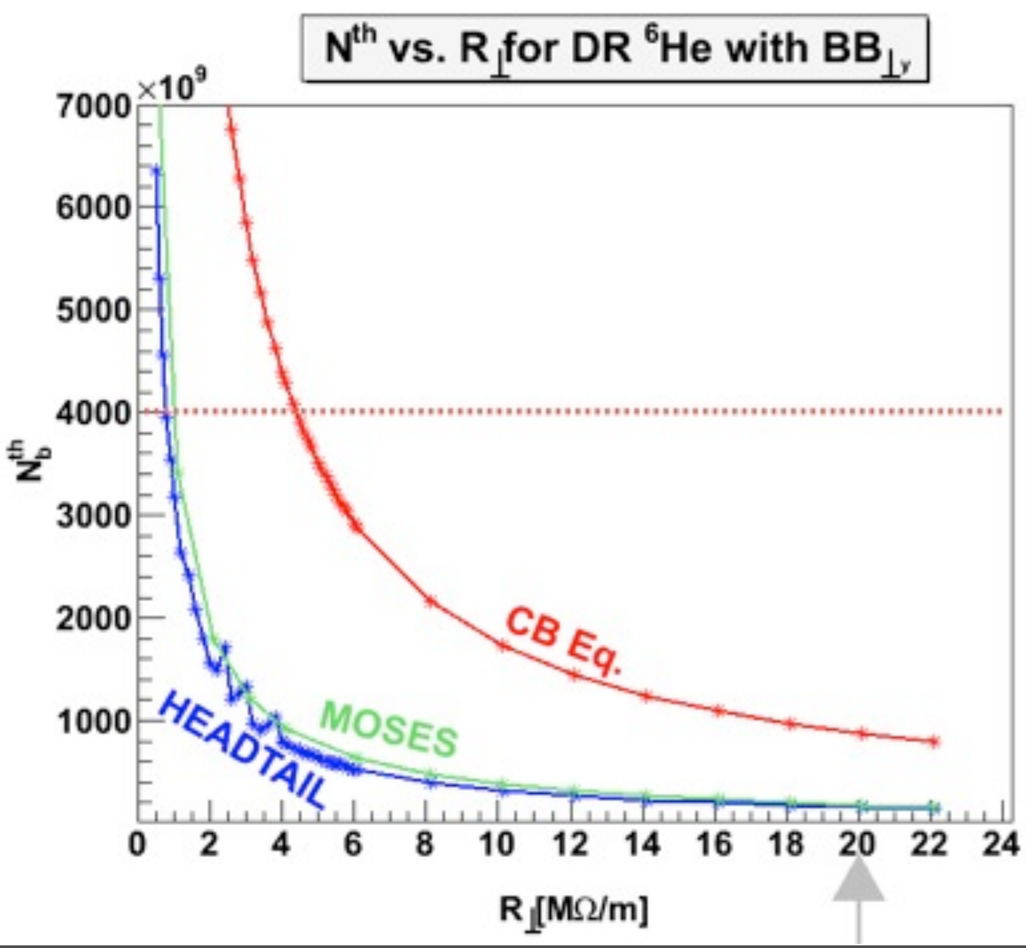

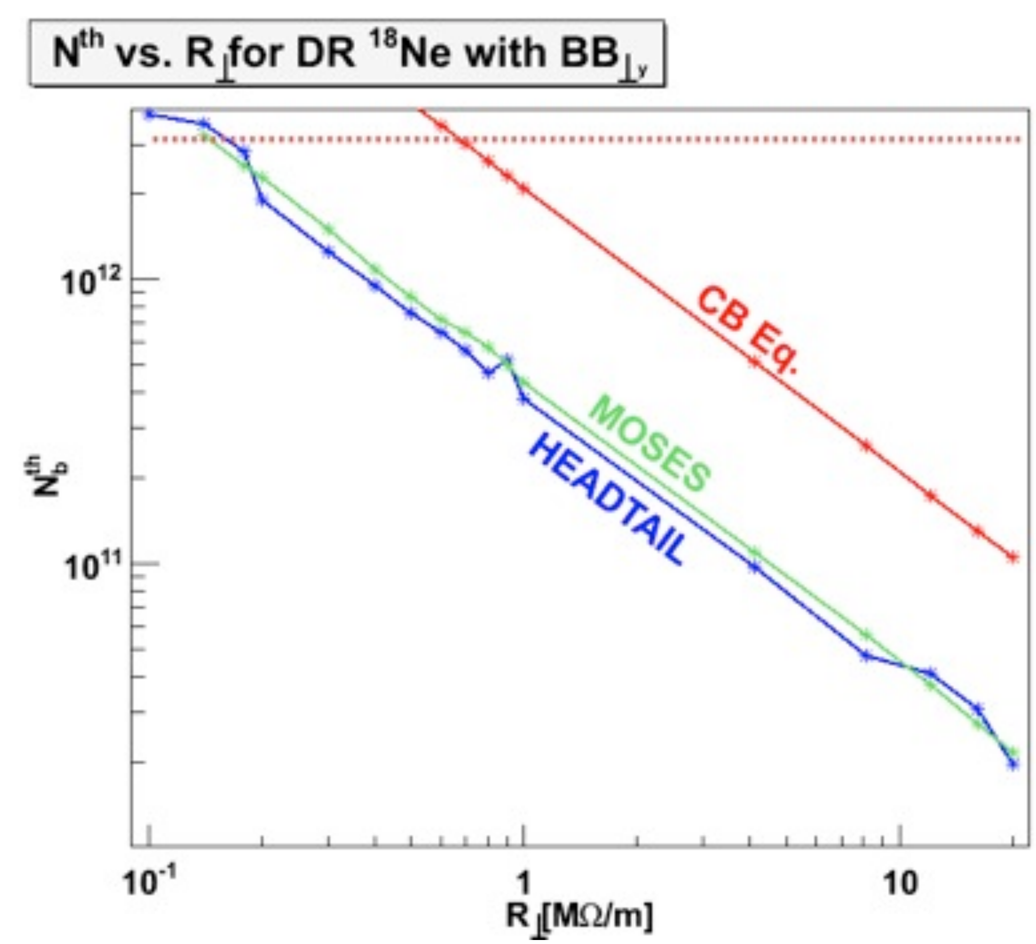

Outline

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- Collective Effects
  - Laslett's Tune Shifts
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Outline

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Conclusion

CONCLUSION

- Direct Space Charge effect will not limit the performance of the Decay Ring (Laslett's Equations)

- We have a very challenging upper limit of the DR's Transversal Shunt Impedance, $R_\perp$:
  - ➡ 10 (100) times smaller than SPS for ^{6}He (^{18}Ne)

… based on HEADTAIL and MOSES studies

- This study, that was completely based on parameters from "FP6", suggests a re-optimization of the Beta Beam design

Note under preparation:
http://chansen.web.cern.ch/chansen/PUBLICATIONS/bbCollective.pdf
SVN: http://svnweb.cern.ch/world/wsvn/bbcollective

Backup Slides

Input Parameters

B A C K U P

TABLE 2. Input parameters from previous Beta Beam Decay Ring design report [10].

Parameters	Description	DR ^{18}Ne	DR ^{6}He
Z	*Charge Number*	10	2
A	*Mass Number*	18	6
h	*Harmonic Number*	924	924
C [m]	*Circumference*	6911.6	6911.6
ρ [m]	*Magnetic Radius*	155.6	155.6
γ_{tr}	*Gamma at Transition*	27.00	27.00
V_{RF} [MV]	*Voltage*	1.196e+01	2.000e+01
dB/dt [T/s]	*Magnetic Ramp*	0.00	0.00
γ	*Relativistic Gamma*	100.0	100.0
δ_{max}	*Maximum Momentum Spread*	2.50e-03	2.50e-03
E_{rest} [MeV]	*Rest Energy*	16767.10	5605.54
M	*Number Bunches per Batch*	20	20
L_b [m]	*Full Bunch Length*	1.970	1.970
N_b	*Number Ions per Injected Bunch*	2.35e+11	4.87e+11
N_B	*Average Number Ions per Bunch*	3.10e+12	4.00e+12
m_r	*Merges Ratio*	20	15
$t_{1/2}$ [s]	*Half Life at Rest*	1.67	0.81
T_c [s]	*Revolution Time*	3.60	6.00
Q_x	*Horizontal Tune*	22.23	22.23
Q_y	*Vertical Tune*	12.16	12.16
$\langle\beta\rangle_x$ [m]	*Average Horizontal Betatron Function*	148.25	148.25
$\langle\beta\rangle_y$ [m]	*Average Vertical Betatron Function*	173.64	173.64
$\langle D\rangle_x$ [m]	*Average Dispersion*	-0.60	-0.60
ξ_x	*Horizontal Chromaticity*	0.0	0.0
ξ_y	*Vertical Chromaticity*	0.0	0.0
$\varepsilon_{N_x}(1\sigma)$ [πm-rad]	*Normalized Horizontal Emittance*	1.48e-05	1.48e-05
$\varepsilon_{N_y}(1\sigma)$ [πm-rad]	*Normalized Vertical Emittance*	7.90e-06	7.90e-06
ε_l (full) [eVs]	*Full Longitudinal Emittance*	42.89	14.36
b_x [cm]	*Horizontal Beam Pipe Size*	16.0	16.0
b_y [cm]	*Vertical Beam Pipe Size*	16.0	16.0
ρ_{res} [Ω m]	*Resistivity*	1.0e-07	1.0e-07

TABLE 3. Assumed impedance input parameters.

Parameters	Description	DR ^{18}Ne	DR ^{6}He
$Q_{\parallel}$	*Longitudinal Quality Factor*	1.00	1.00
$\omega_{r,\parallel}$ [GHz]	*Longitudinal Angular Resonance Frequency*	6.28	6.28
$\left\|Z_{\parallel}/n\right\|$ [Ω] $= \lim_{\omega\to 0} \frac{\|Z(\omega)\|}{\omega/\omega_{rev}}$		10.00	10.00
$R_{s,\parallel}$ [MΩ] $= \frac{\|Z/n\| Q \omega_r}{\omega_{rev}}$	*Longitudinal Shunt Impedance*	0.231	0.231
$Q_{\perp}$	*Transverse Quality Factor*	1.00	1.00
$\omega_{r,\perp}$ [GHz]	*Transverse Angular Resonance Frequency*	6.28	6.28
$R_{s,\perp}$ [$M\Omega/m$]	*Transverse Shunt Impedance*	20.00	20.00

Calculated Values

B A C K U P

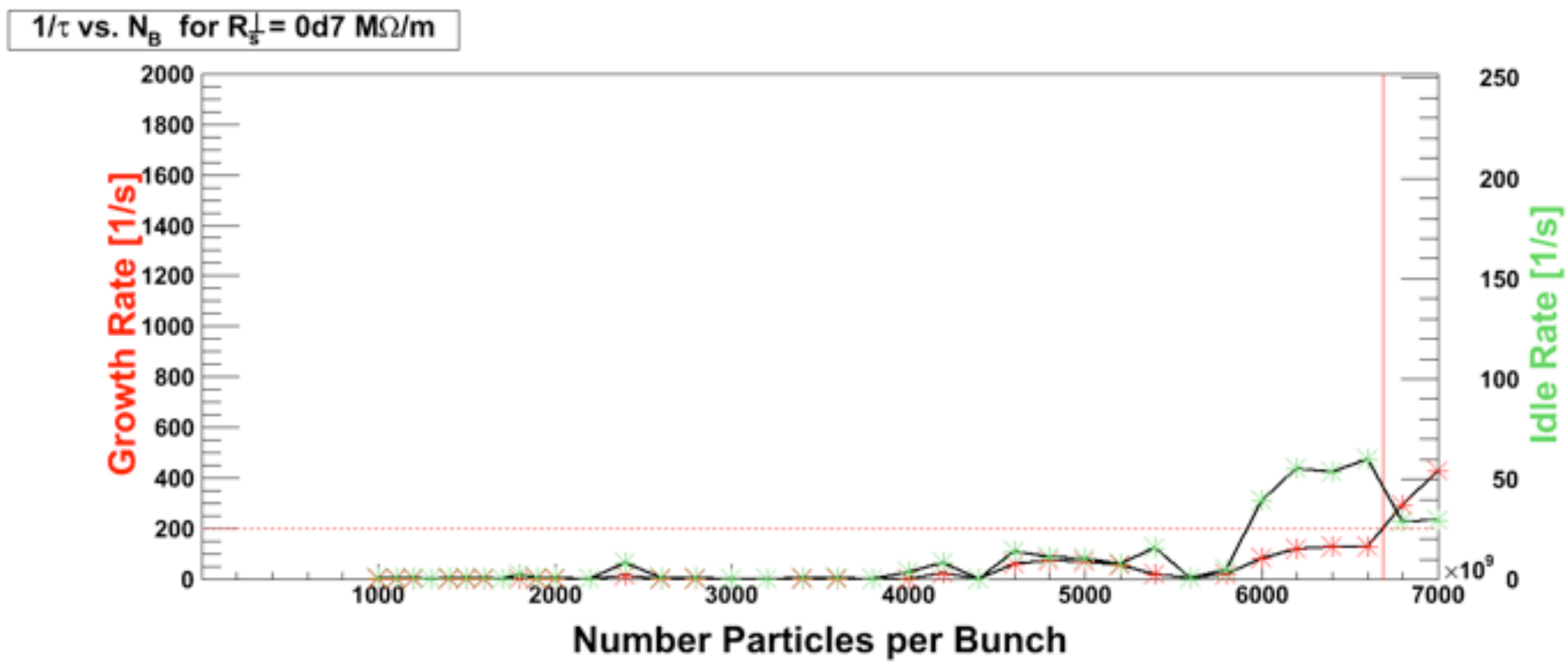
TABLE 4. Calculated values.

		DR ^{18}Ne	DR ^{6}He
r_0 [m] $= r_p Z^2/A$	*Ion Radius*	8.53e-18	1.02e-18
E_{tot} [GeV] $= \gamma \cdot E_{rest}$	*Total Energy*	1676.71	560.55
$\beta = \sqrt{1-1/\gamma^2}$	*Relativistic Beta*	1.00	1.00
$\eta = (1/\gamma_{tr})^2 - (1/\gamma)^2$	*Phase Slip Factor*	1.27e-03	1.27e-03
T_{rev} [μ s] $= C/(\beta c)$	*Revolution Time*	23.0558	23.0558
R [m] $= C/2\pi$	*Machine Radius*	1100.02	1100.02
ω_{rev} [MHz] $= 2\pi/T_{rev}$	*Angular Revolution Frequency*	0.27	0.27
$\sigma_\delta = \delta_{max}/2$	*1 Sigma Momentum Spread*	1.25e-03	1.25e-03
τ_b [ns] $= L_b/(\beta c)$	*Full Bunch Length*	6.57	6.57
$\hat{I}$ [A] $= ZeN_B/\tau_b$	*Peak Current*	755.80	195.04
I_b [A] $= ZeN_B/T_{rev}$	*Beam Current*	0.22	0.06
$\varepsilon_l^{2\sigma}$ [eVs] $= \frac{\pi}{2}\beta^2 E_{tot}\tau_b\delta_{max}$	*2 Sigma Longitudinal Emittance*	43.27	14.46
$Q_s = \sqrt{\frac{hZeV\vert\eta\cos\phi_s\vert}{2\pi\beta^2 E_{tot}}}$	*Synchrotron Tune*	0.00	0.00
ω_s [kHz] $= Q_s \cdot \omega_{rev}$	*Synchrotron Angular Frequency*	1.00	1.00
ω_x [MHz] $= Q_x \cdot \omega_{rev}$	*Horizontal Betatron Angular Frequency*	6.06	6.06
ω_y [MHz] $= Q_y \cdot \omega_{rev}$	*Vertical Betatron Angular Frequency*	6.06	6.06
ω_c [GHz] $= \beta c/b_{min(x,y)}$	*Cut-Off Angular Frequency*	1.87	1.87
$\Delta Q_{\xi_x} = \xi_x \delta_{max} Q_x$	*Horizontal Tune Shift due to Chromaticity*	0.0	0.0
$\Delta Q_{\xi_y} = \xi_y \delta_{max} Q_y$	*Vertical Tune Shift due to Chromaticity*	0.0	0.0
ω_{ξ_x} [MHz] $= \xi_x Q_x \omega_{rev}/\eta$	*Horizontal Chromatic Angular Frequency*	2.38e+02	2.38e+02
ω_{ξ_y} [MHz] $= \xi_y Q_y \omega_{rev}/\eta$	*Vertical Chromatic Angular Frequency*	1.30e+02	1.30e+02

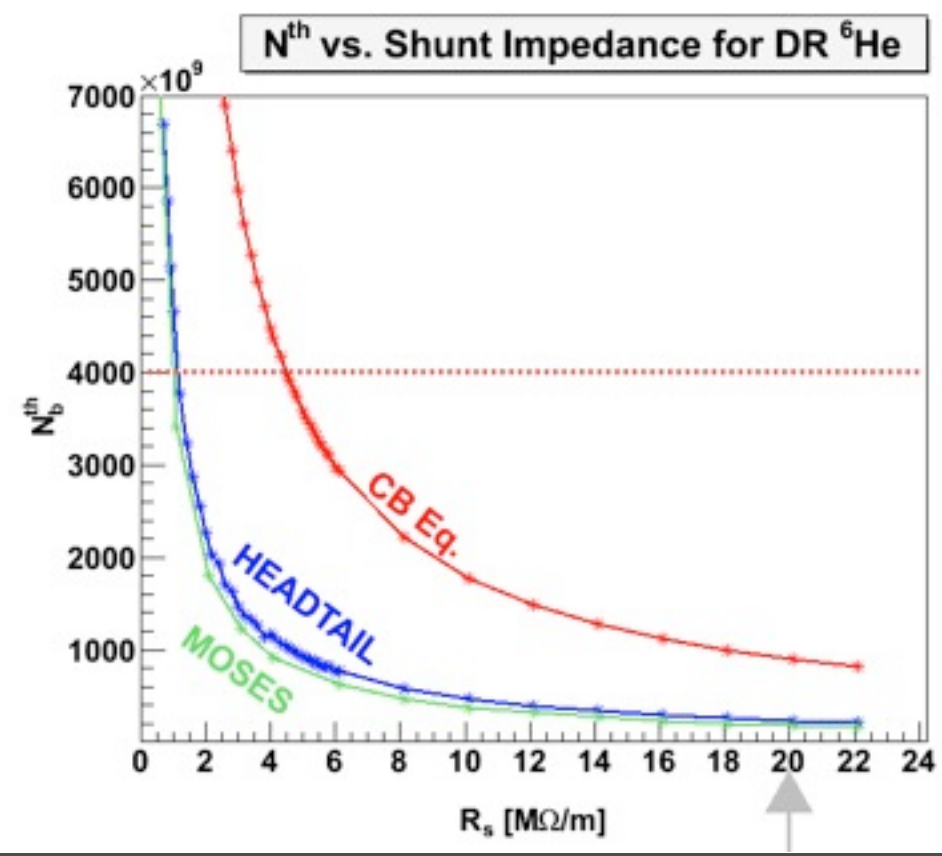
N_b^{th} vs. $R_\perp$ for ^6He in DR

COLLECTIVE

- **$N_b > N_b^{th}$ when rise times < 5 ms** (growth rate > 200 Hz)
- **G.R. vs. N_b^{th} for different $R_\perp$ →**



- **$R_\perp$ could be lowered to increase the intensity limit**
- **But a factor 10 smaller than $R_\perp^{sps}$ = 20 MΩ/m is <u>very</u> challenging**



MOSES is developed for protons, so to get the ion equivalent the intensity limits, N^{th}_{moses}, was divided by a factor Z

N_b^{th} vs. $R_\perp$ for ^{6}He in DR

C O L L E C T I V E

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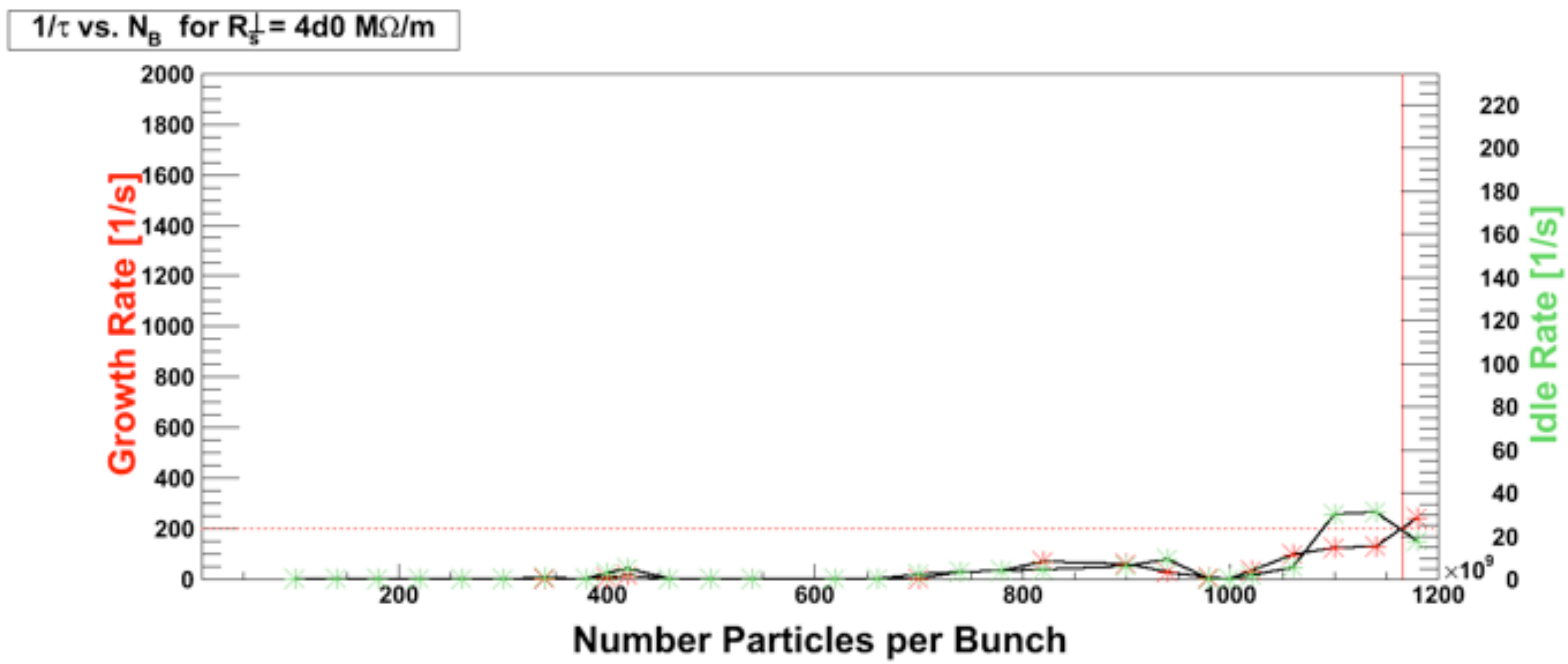

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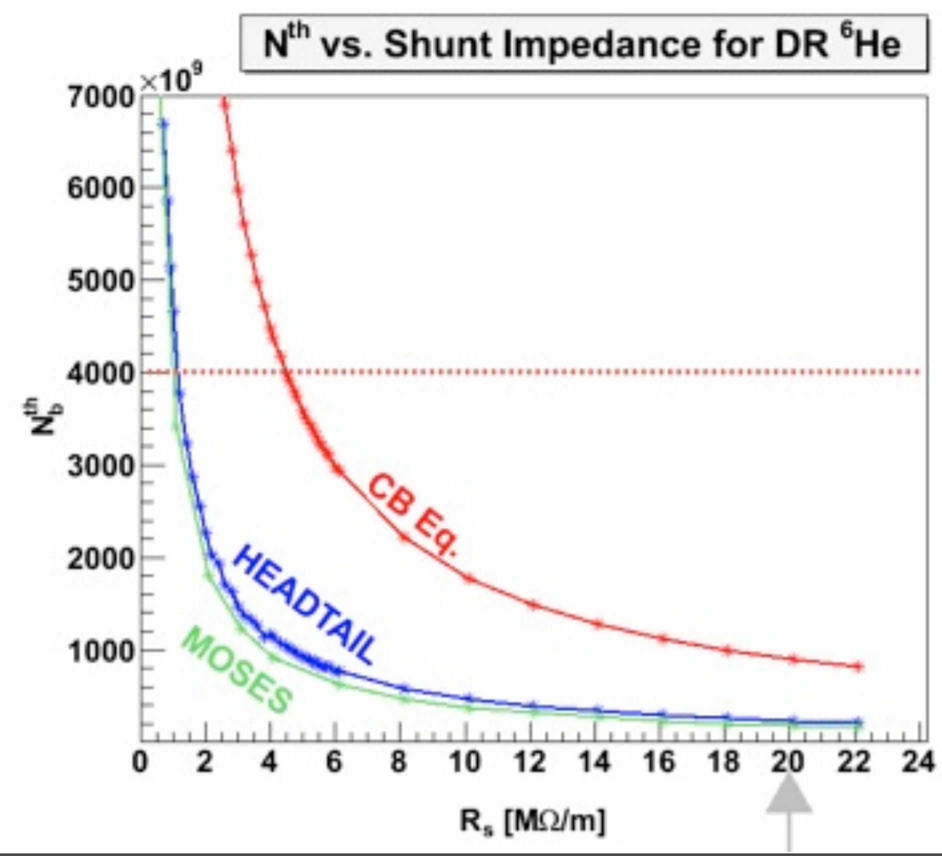

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N_b^{th} vs. $R_\perp$ for ^{18}Ne in DR

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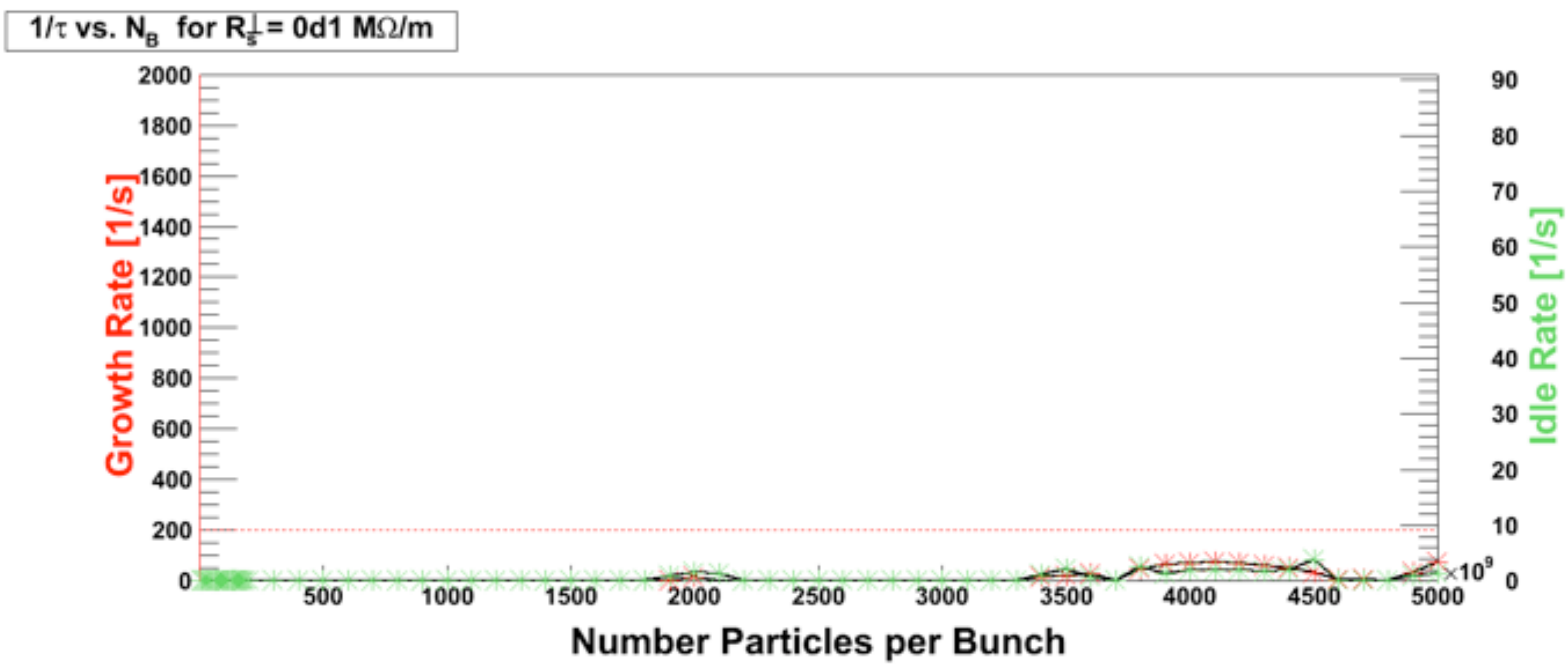
- **G.R. vs. N_b^{th} for different $R_\perp$ →**



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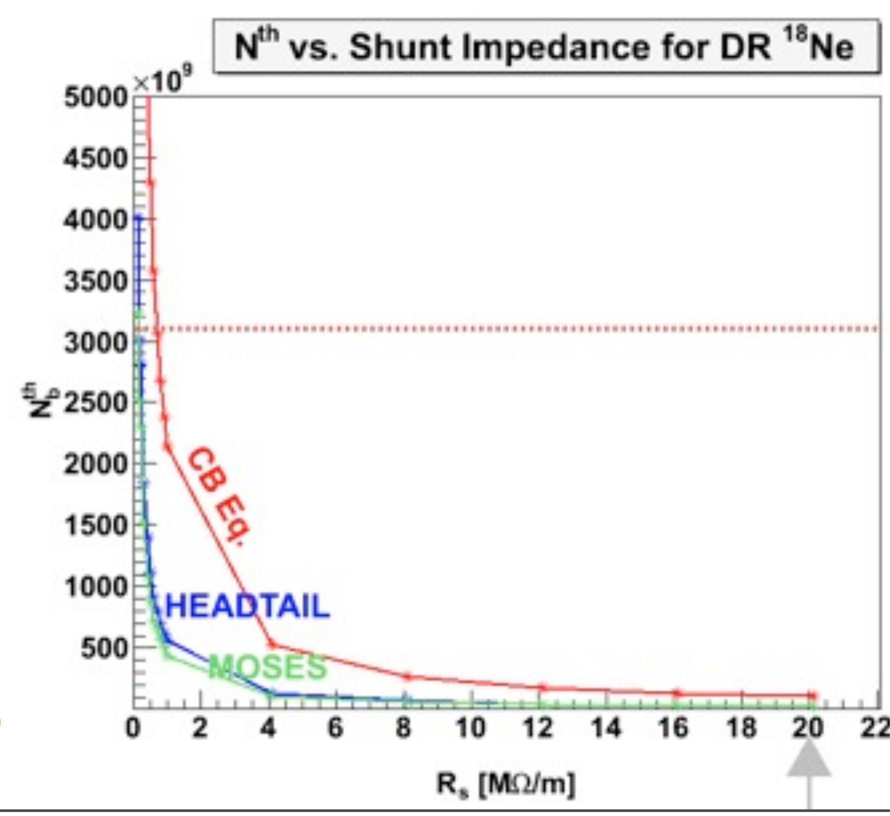

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COLLECTIVE

N_b^{th} vs. $R_\perp$ for ^{18}Ne in DR

COLLECTIVE

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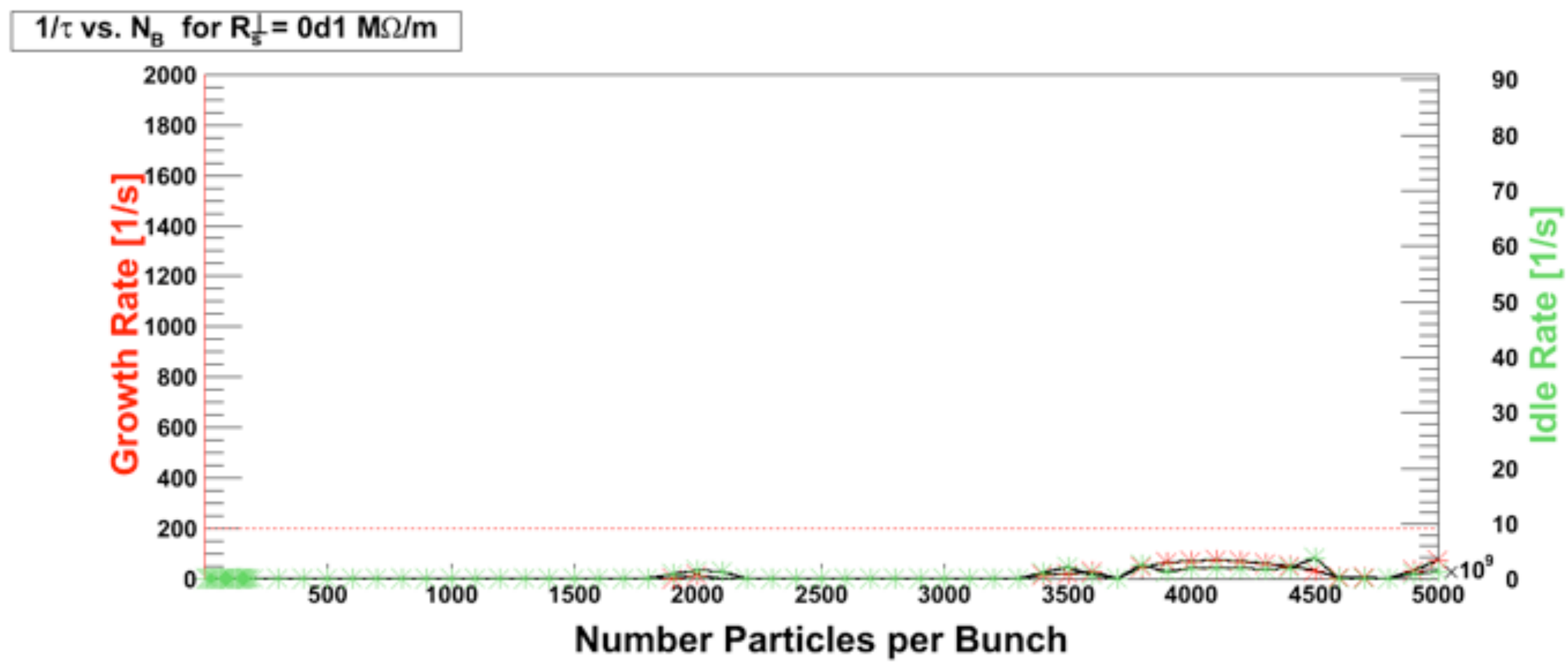

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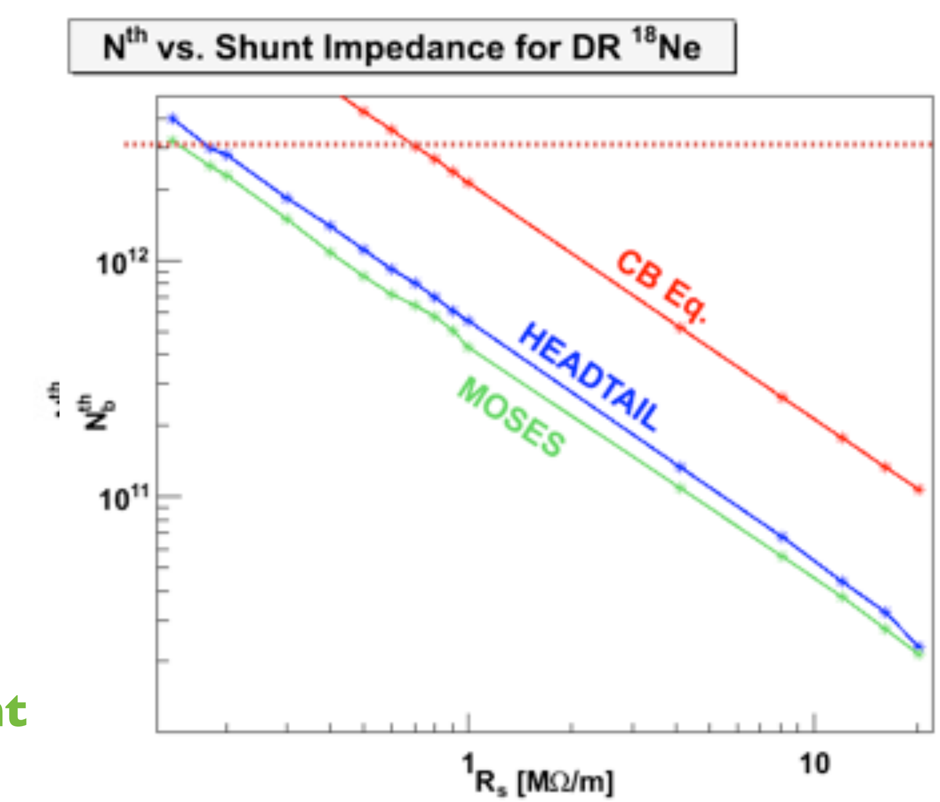

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Growth Rate From Eq. of Motion

CHALLENGES

$$\ddot{y} + (Q_y \omega_{rev})^2 y = 0$$

$$\ddot{y} + (Q_y \omega_{rev})^2 y = Ky$$

$$y(t) = A_1 e^{i(Q_y + \Delta Q_y)\omega_{rev} t} + A_2 e^{-i(Q_y + \Delta Q_y)\omega_{rev} t}$$

$$\Delta Q_y = -K / \left(2 Q_y \omega_{rev}^2\right)$$

$$\begin{aligned} \bar{y}(t) &= A e^{i(Q_y + \Delta Q_y)\omega_{rev} t} \\ &= A e^{i(Q_y + \Re[\Delta Q_y])\omega_{rev} t} e^{-\Im[\Delta Q_y]\omega_{rev} t} \end{aligned}$$

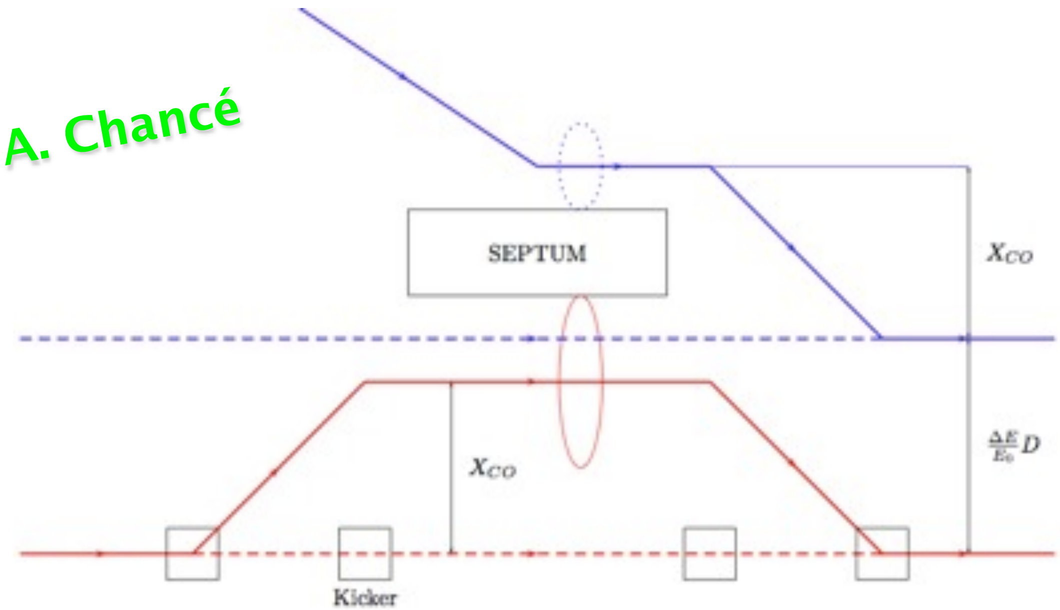
$$1/\tau \equiv -\Im\left[\Delta Q_y\right] \omega_{rev}$$

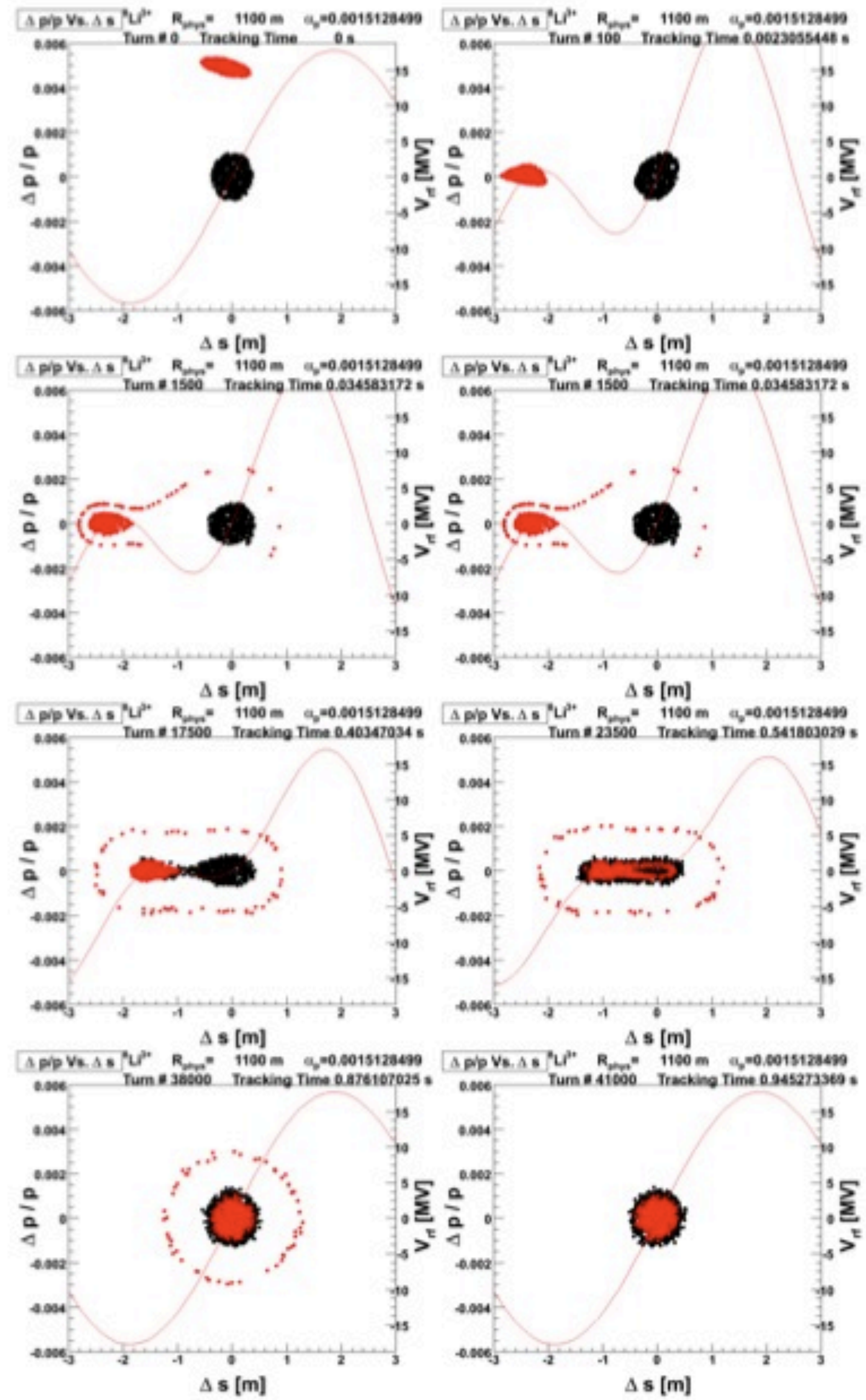
DR: Injection Scheme

Daniel C. Heinrich

- **The new bunch is injected off momentum** (separated by a septum magnet)

A. Chancé





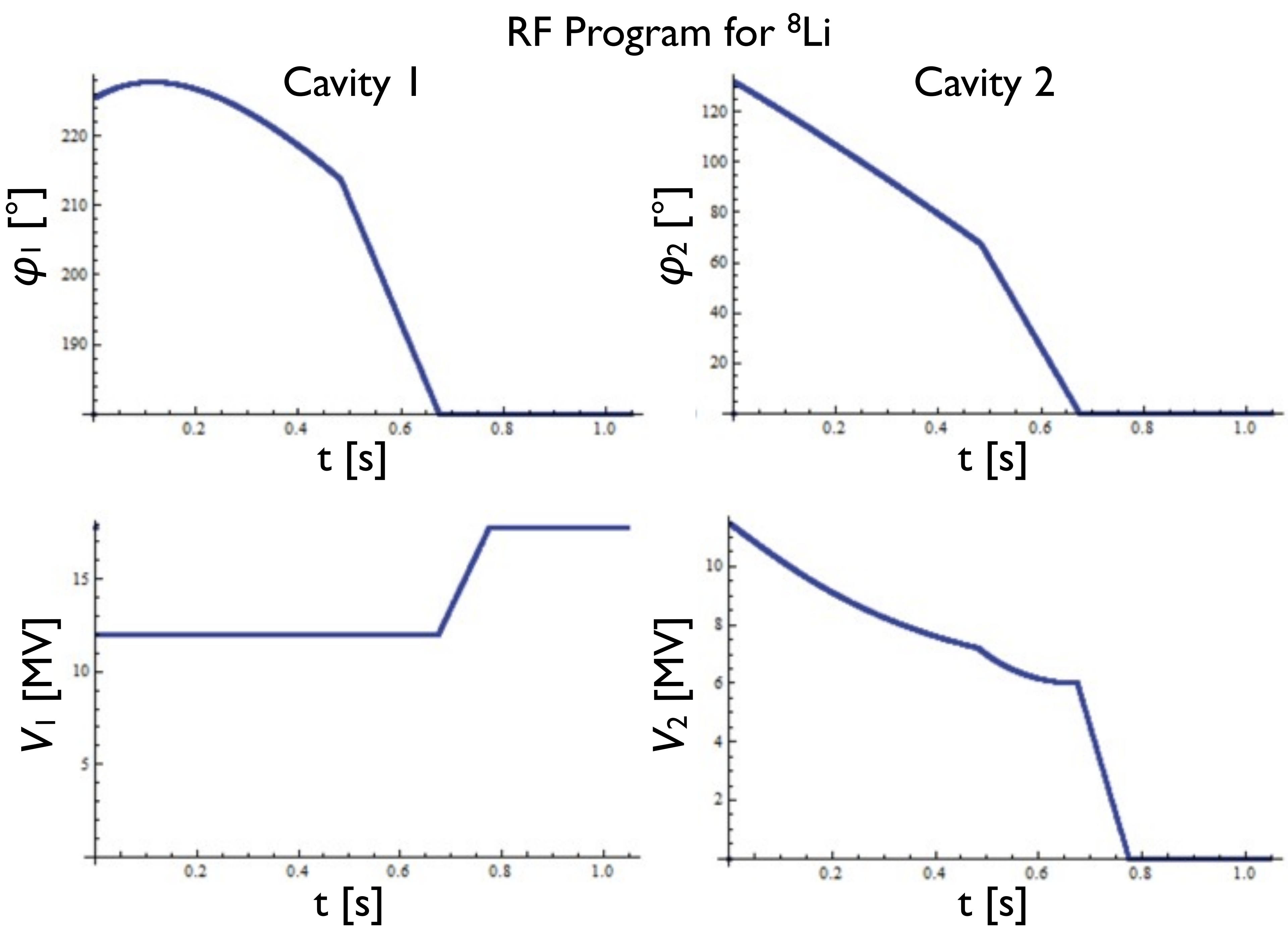
- **After ¼ synchrotron turn it is "captured" by one RF system**
- **Then "merged" into the old bunch with the use of a 2nd RF system**
- **Collimation at Δp/p = 2.5‰**
  - ➡ **scrapes away ions not captured**
  - ➡ **limits the bunch size to protect the septum magnet**

DR: RF Program

Daniel C. Heinrich

A. Chancé

- **The**



DR: RF Program