Beta Beams,
EUROnu WP4

SEVENTH FRAMEWORK PROGRAMME

One of the Beta Beam Challenges:

Collective Effects

Christian Hansen

20/01/2011, EUROnu Annual Meeting, RAL

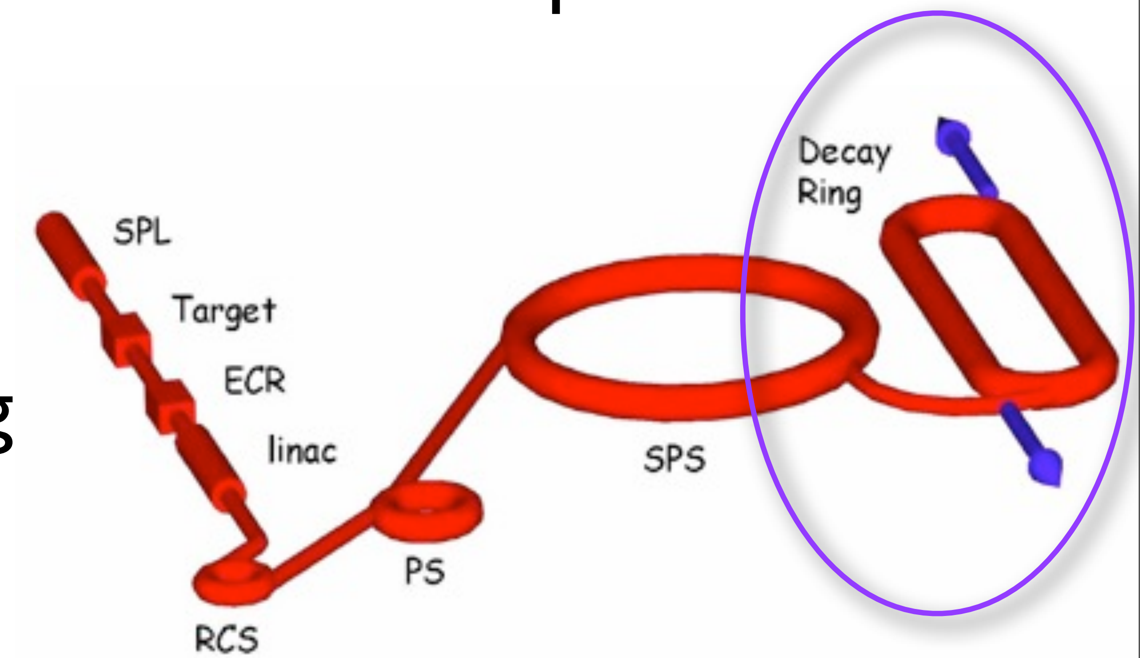
Many thanks to: E. Benedetto, A. Chancé, K. Li, E. Metral, N. Mounet, G. Rumolo, B. Salvant & E. Wildner

BB Collective Effects Studies

COLLECTIVE

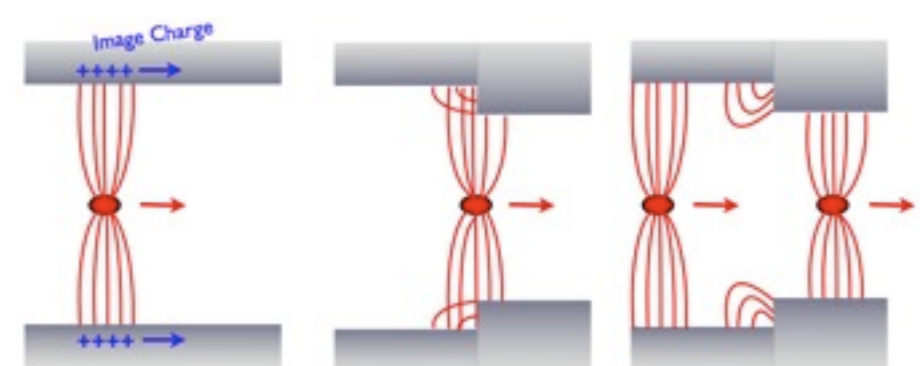
- Instability studies are important for the Beta Beam project, since
  - ➡ High intensity ion beams are foreseen
  - ➡ Collective Effects could limit the final performance

- Will study all machines
  - ➡ Today <u>only</u> the Decay Ring



- Will study all possible reasons for instabilities
  - ➡ Today <u>only</u> results from single bunch

"Transverse Resonance Broad Band Impedance"



3 Tools

- Three ways to find the Bunch Intensity Limit, N_b^{th}:
  - ➡ A multi-particle tracking program in time domain, "HEADTAIL"

    G. Rumolo et ali, CERN-SL-Note2002-036-AP
  - ➡ A theoretical program in frequency domain, "MOSES"

    Y.H.Chin CERN-LEP-TH/88-05
  - ➡ Peak current values into a coasting beam formula gives the "Coasting Beam Equation" (here for ξ=0):

$$N_{b_{x,y}}^{th} = \frac{32}{3\sqrt{2}\pi} \frac{R|\eta|\varepsilon_l^{2\sigma}\omega_r}{\langle\beta\rangle_{x,y} Z^2\beta^2 c R_\perp}$$

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

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$R_\perp$ = "Shunt Impedance" (see next slide)

$R_\perp$ of the DR

Private Discussions with G. Rumolo

IMPEDANCE

- Detailed calculations of Transversal Shunt Impedance, $R_\perp$, require design assumptions of ALL DR components, instead:
- **Let's estimate $R_\perp^{DR}$ based on a machine with same circumference as DR; SPS ($R_\perp^{SPS}$ = 20 MΩ/m)**
  - ➡ **Modern, smooth design of the vacuum pipe compare to old SPS → *Improvement by factor 10***

    → $R_\perp^{DR}$ ~ 2 MΩ/m
  - ➡ **The DR is a less general machine than the SPS** (not required to handle many type of beams)
  - ➡ **No need for as many kickers as SPS** (and modern kicker design) → ***Improvement by factor 2***

    → $R_\perp^{DR}$ ~ 1 MΩ/m
- Further; in 20 years improved Broad Band Feedback System

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

C. Hansen, CERN, NUFACT10
Collective Effect Studies of a Beta Beam Decay Ring

THRESHOLD

- **According to the Coasting Beam Equation (CB Eq.) $R_\perp$ is the only parameter not fixed by FP6 design**
- **Let's find required shunt impedance, $R_\perp^{req}$;**

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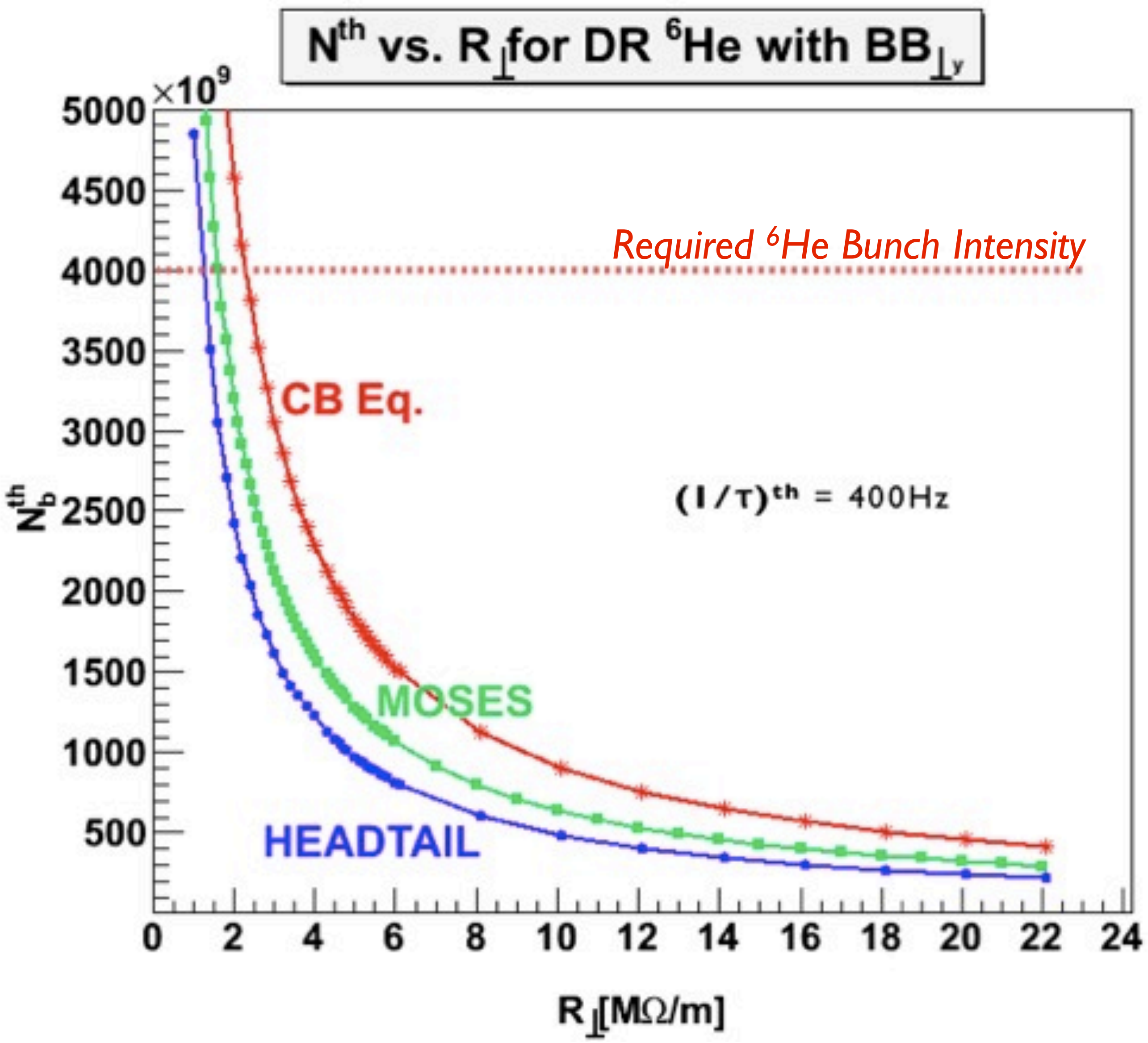

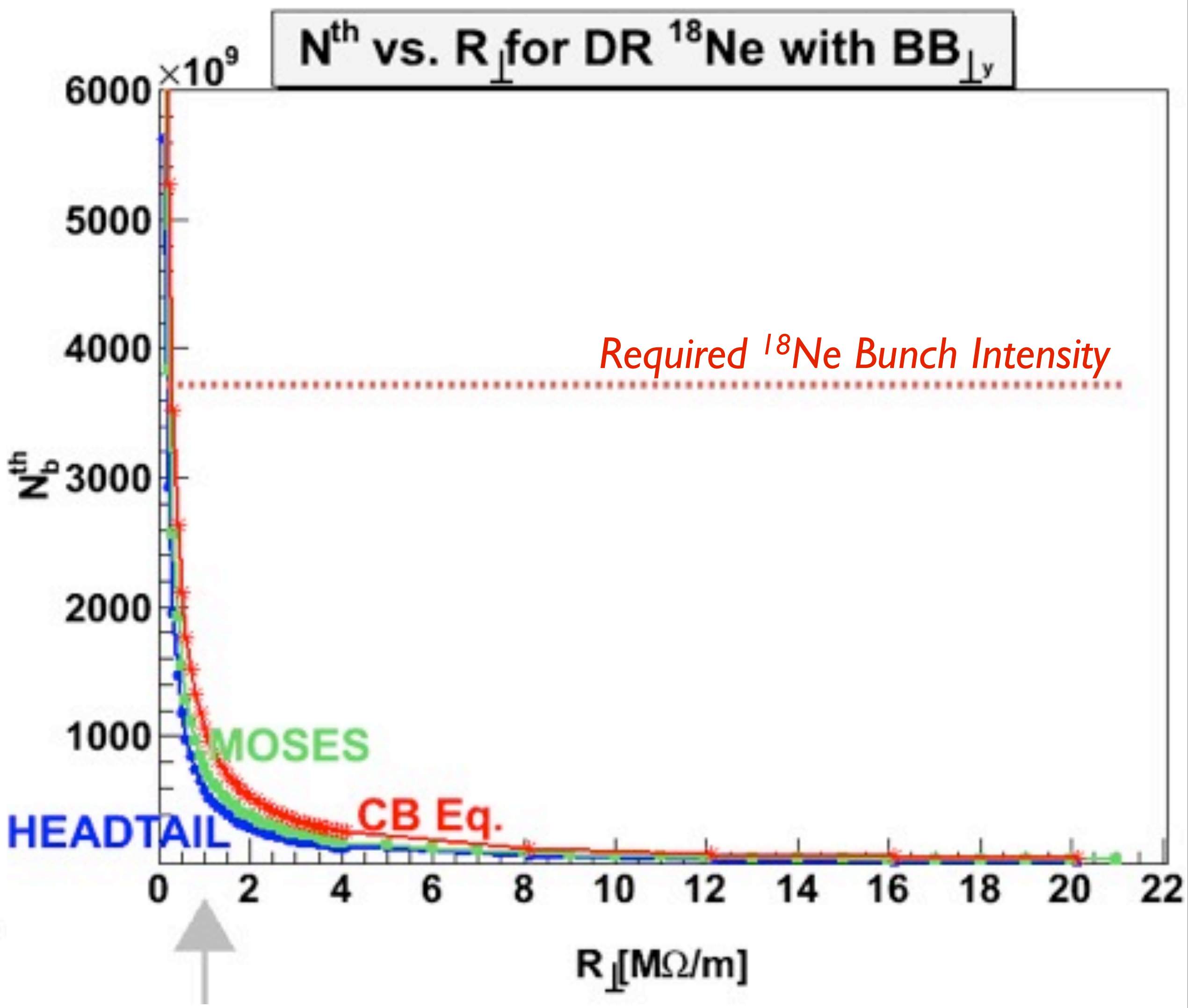

N_b^{th} vs. $R_\perp$ in DR

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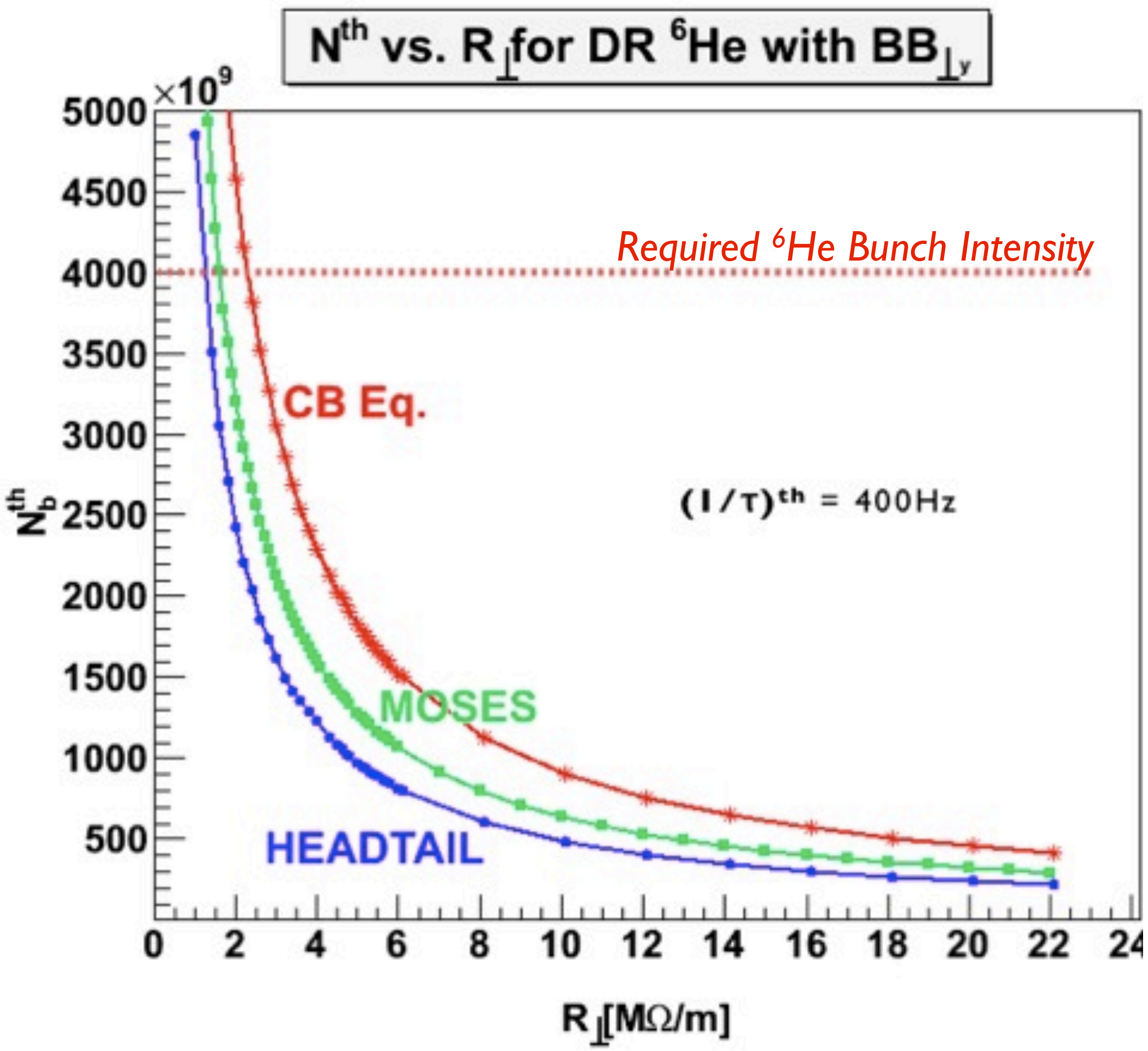

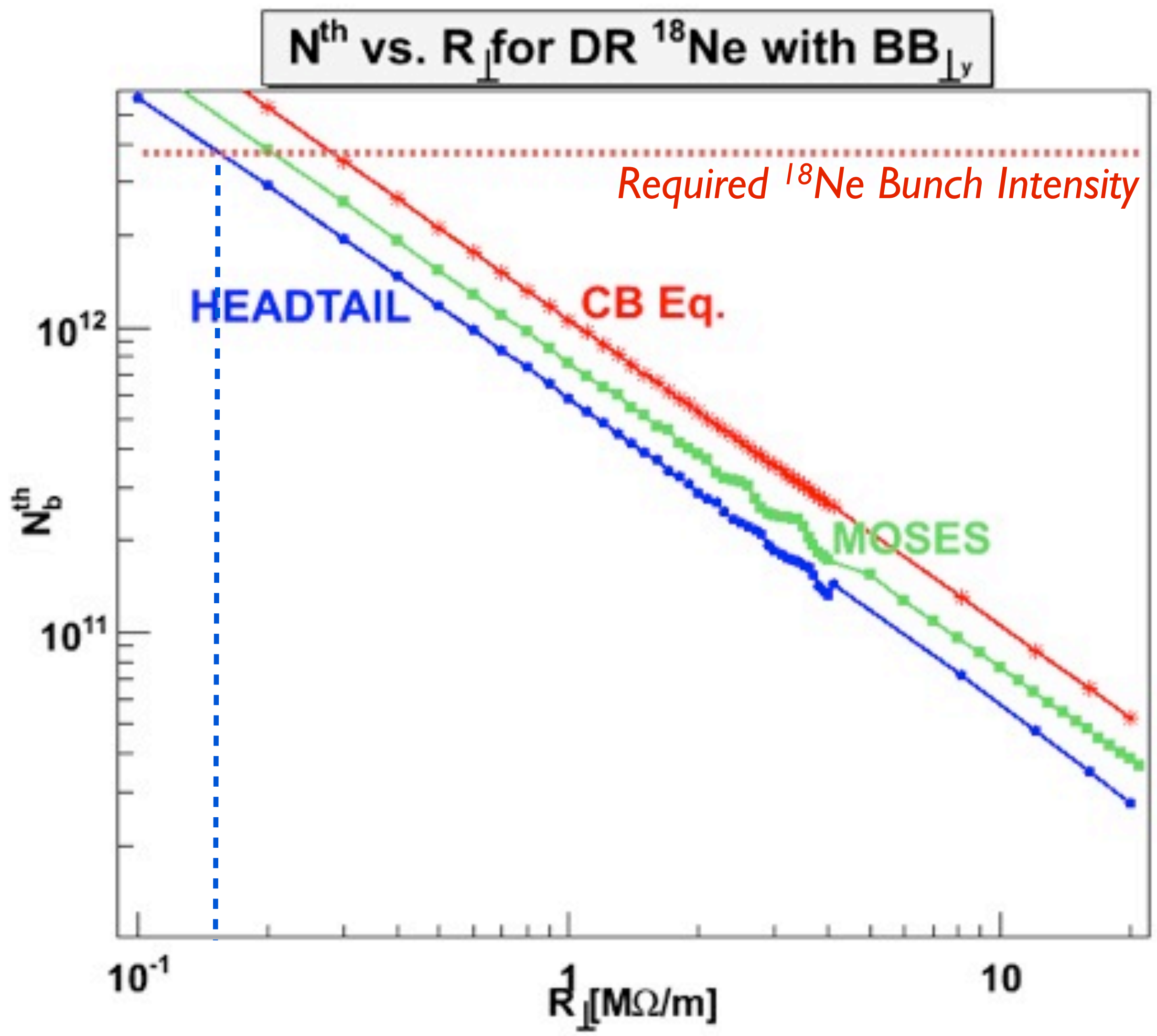

- **$R_\perp^{req}$ = 0.15 MΩ/m to allow N_b^{th} = 3e12 ^{18}Ne So since $R_\perp^{req} < R_\perp^{DR} \sim 1$ MΩ/m → Redesign of DR**

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

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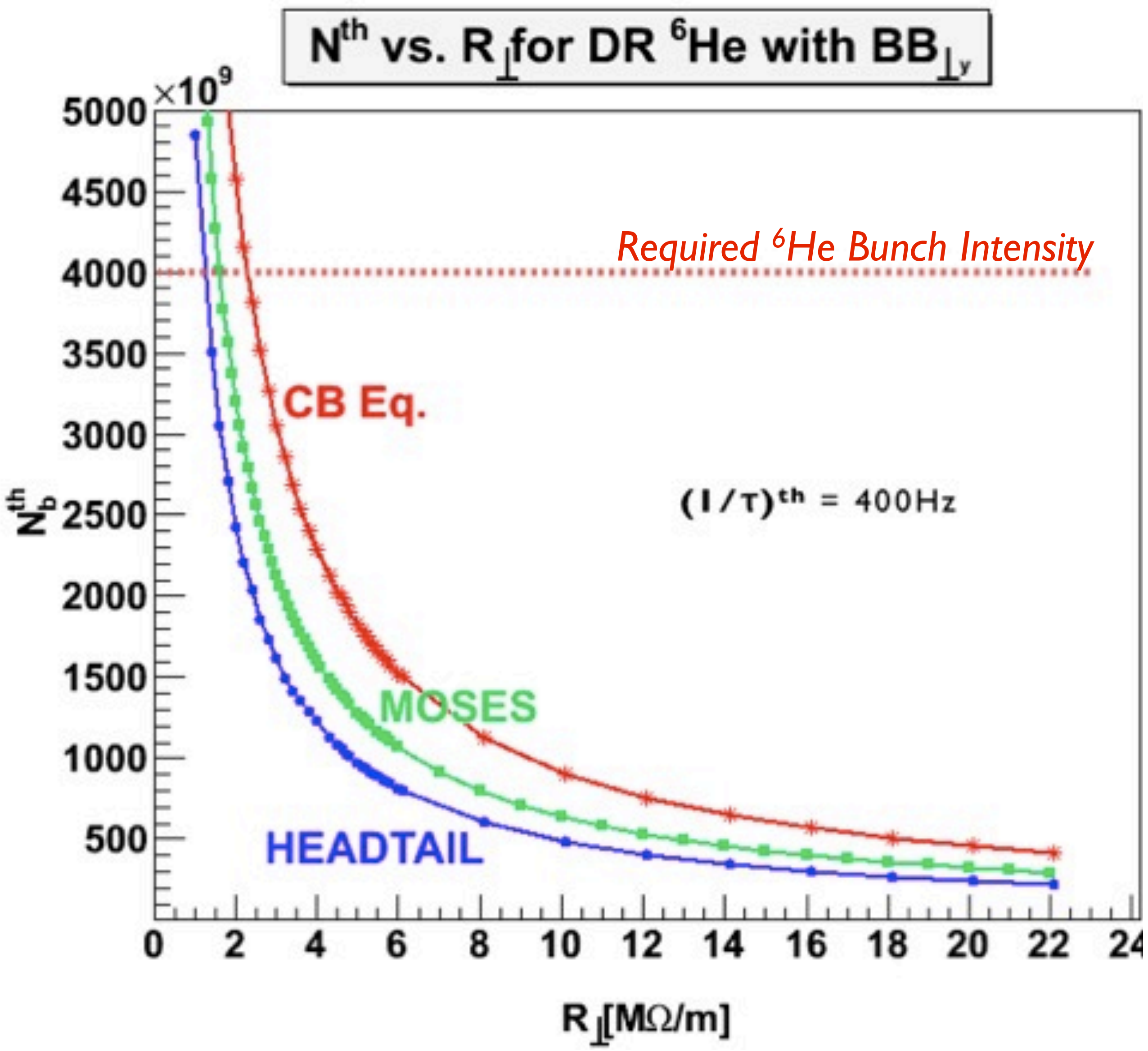
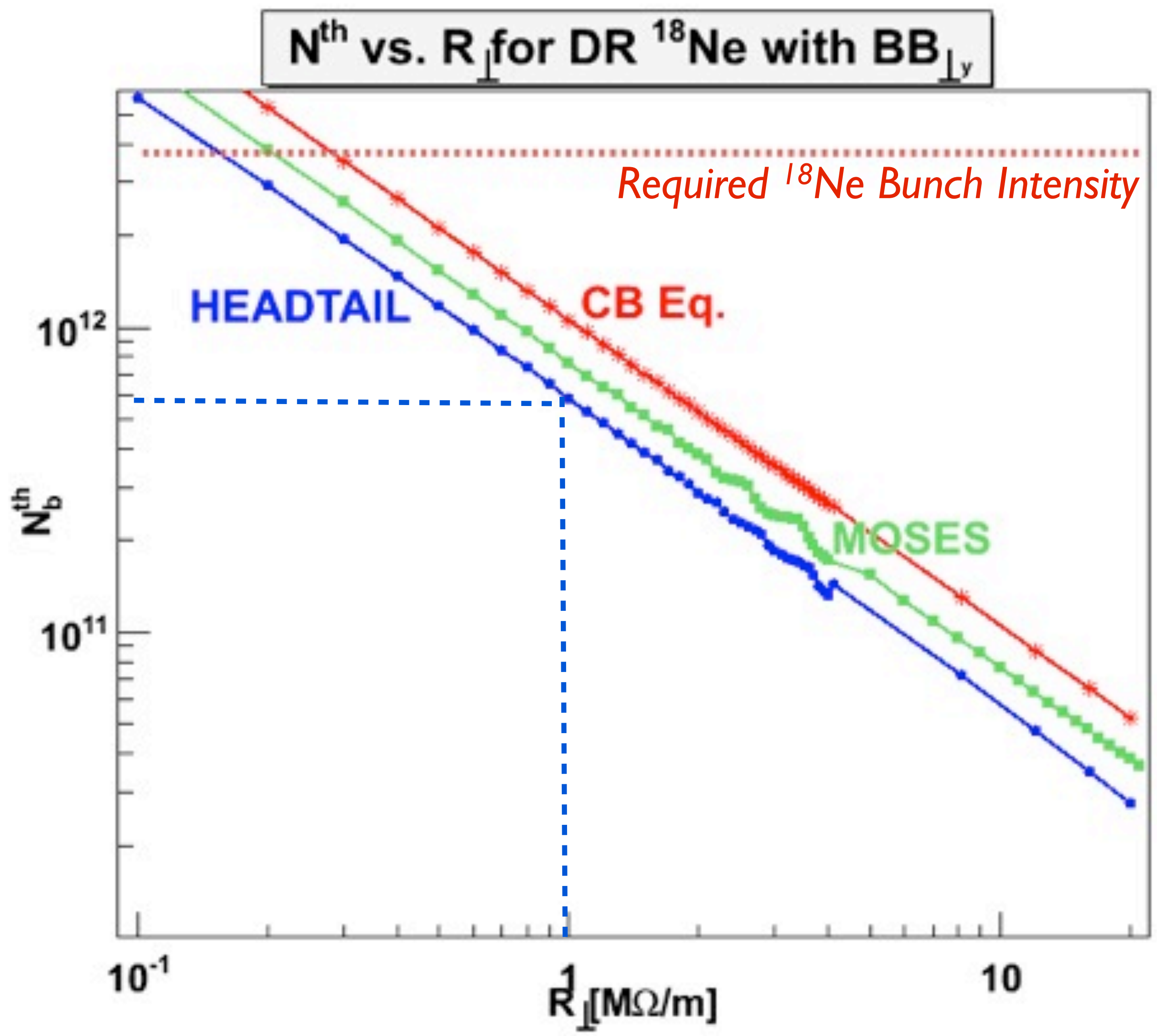




- **N_b^{th} = 6e11 ^{18}Ne can be used to get N_b^{th} for all other ions by using that CB Eq. goes as** $N_{b_{x,y}}^{th} \propto \frac{A}{Z^2}$

DR Intensity Limit for FP6 Lattice

ALL IONS

$R_\perp^{DR}$ = 1 MΩ/m	Bunch Intensity Limit, N_b^{th} [e12]	[% of N_b^{nom}]
^{6}He	5.0	100
^{18}Ne	0.6	16
^{6}He	5.0	52
^{18}Ne	0.6	32
^{6}He	5.0	52
^{18}Ne	0.6	81
^{8}Li	3.0	60
^{8}B	1.1	59
^{8}Li	3.0	30
^{8}B	1.1	29
^{8}Li	3.0	12
^{8}B	1.1	12

^{8}Li	^{8}B	^{6}He
60	59	100
30	29	50
12	12	21

$$N_b^{nom} = \frac{\Phi_0 L_{circ} t_{sps}}{N_{bunches} L_{eff} T_{eff}^{year}} \left(1 - 2^{-\frac{t_{sps}}{\gamma t_{1/2}}}\right)^{-1}$$

Note; In Donini's table SF = 10^{-4} while we are using SF = $5 \cdot 10^{-3}$

A. Donini, Summary on Beta-Beams

Ions	Fluxes [10^{18}]	Years	$(\sin^2 2\theta_{13})_{min}$	NH,$(\sin^2 2\theta_{13})_{min}$
^{6}He ^{18}Ne	$\bar{\Phi}_0 = 2.9$ $\Phi_0 = 1.1$	5 5	5×10^{-4}	No Sensitivity
^{6}He ^{18}Ne	$\bar{\Phi}_0 \times 2$ $\Phi_0/2$	2 8	6×10^{-4}	No Sensitivity
^{6}He ^{18}Ne	$\bar{\Phi}_0 \times 2$ $\Phi_0/5$	2 8	1×10^{-3}	No Sensitivity
^{8}Li ^{8}B	$\bar{\Phi}_0$ Φ_0	5 5	1.5×10^{-3}	3×10^{-2}
^{8}Li ^{8}B	$\bar{\Phi}_0 \times 2$ $\Phi_0 \times 2$	5 5	7×10^{-4}	1.5×10^{-2}
^{8}Li ^{8}B	$\bar{\Phi}_0 \times 5$ $\Phi_0 \times 5$	5 5	2×10^{-4}	8×10^{-3}
^{8}Li ^{8}B ^{6}He	$\bar{\Phi}_0$ Φ_0 $\bar{\Phi}_0$	3 5 2	1.7×10^{-3}	3×10^{-2}
^{8}Li ^{8}B ^{6}He	$\bar{\Phi}_0 \times 2$ $\Phi_0 \times 2$ $\bar{\Phi}_0 \times 2$	3 5 2	7×10^{-4}	1.5×10^{-2}
^{8}Li ^{8}B ^{6}He	$\bar{\Phi}_0 \times 5$ $\Phi_0 \times 5$ $\bar{\Phi}_0 \times 5$	3 5 2	3×10^{-4}	8×10^{-3}

Beyond FP6

Decay Ring Redesign

DR REDESIGN

- So far all studies based on EURISOL FP6 parameters

Data Base:
http://j2eeps.cern.ch/beta-beam-parameters/

- According to CB Eq.

$$N^{th}_{b_{x,y}} = \frac{32}{3\sqrt{2}\pi} \frac{R|\eta|\varepsilon_l^{2\sigma}\omega_r}{\langle\beta\rangle_{x,y} Z^2\beta^2 c R_\perp}$$

if we increase the slip-factor, |η|, the bunch intensity limit would increase

- → Redesign of the DR lattice to increase |η| which also increases the average beta function:

A. Chancé, next talk

$$\left.\begin{matrix}\gamma_{tr} = 27 \\ \rightarrow \\ \gamma_{tr} = 18.57\end{matrix}\right\} \quad \left\{\begin{matrix} |\eta_1| = 0.00127 & \rightarrow & |\eta_2| = 0.00276 \\ \langle\beta\rangle_{y1} = 173.64 \text{ m} & \rightarrow & \langle\beta\rangle_{y2} = 160.4 \text{ m}\end{matrix}\right.$$

- → N_b^{th} increase by factor $(\eta_2/\eta_1)/(\beta_2/\beta_1)$

$$\frac{Q_s \beta c \tau_b}{2R|\eta|\delta_{max}} = 1$$

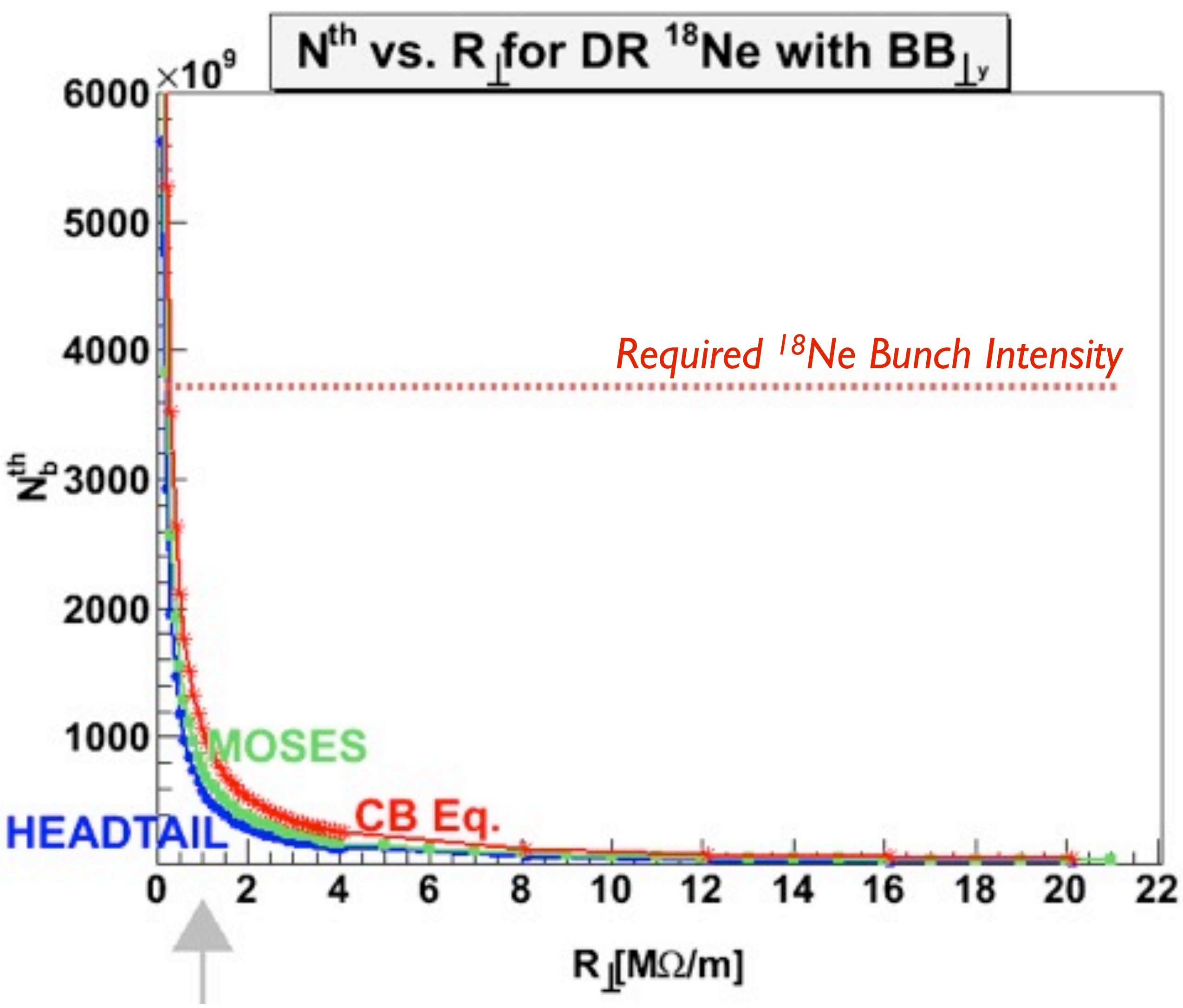
$$Q_s = \sqrt{\frac{hZeV_{rf}|\eta|}{2\pi\beta^2 E_{tot}}}$$

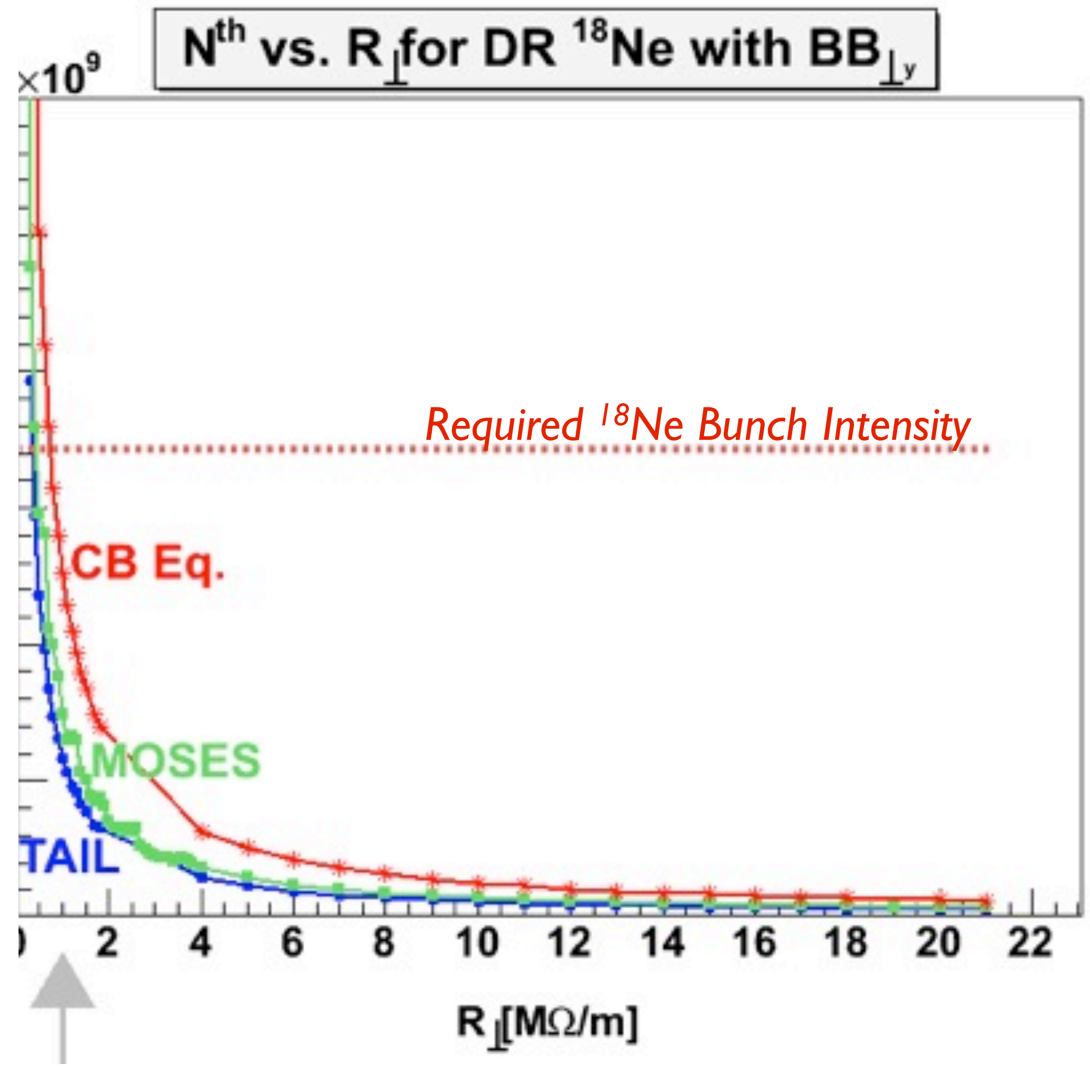
- Matching the bunch in the bucket:
→ Increase voltage by factor η_2/η_1

$$V_{rf} = 26.75 \text{ MV}$$

Decreasing γ_{tr}, Increasing V_{rf}

$$\gamma_{tr} = 27.0 \rightarrow \gamma_{tr} = 18.6$$
$$V_{rf} = 11.96\ \text{MV} \rightarrow V_{rf} = 26.75\ \text{MV}$$
$$L_{eff} = 36\% \rightarrow L_{eff} = 39\%$$





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DR REDESIGN

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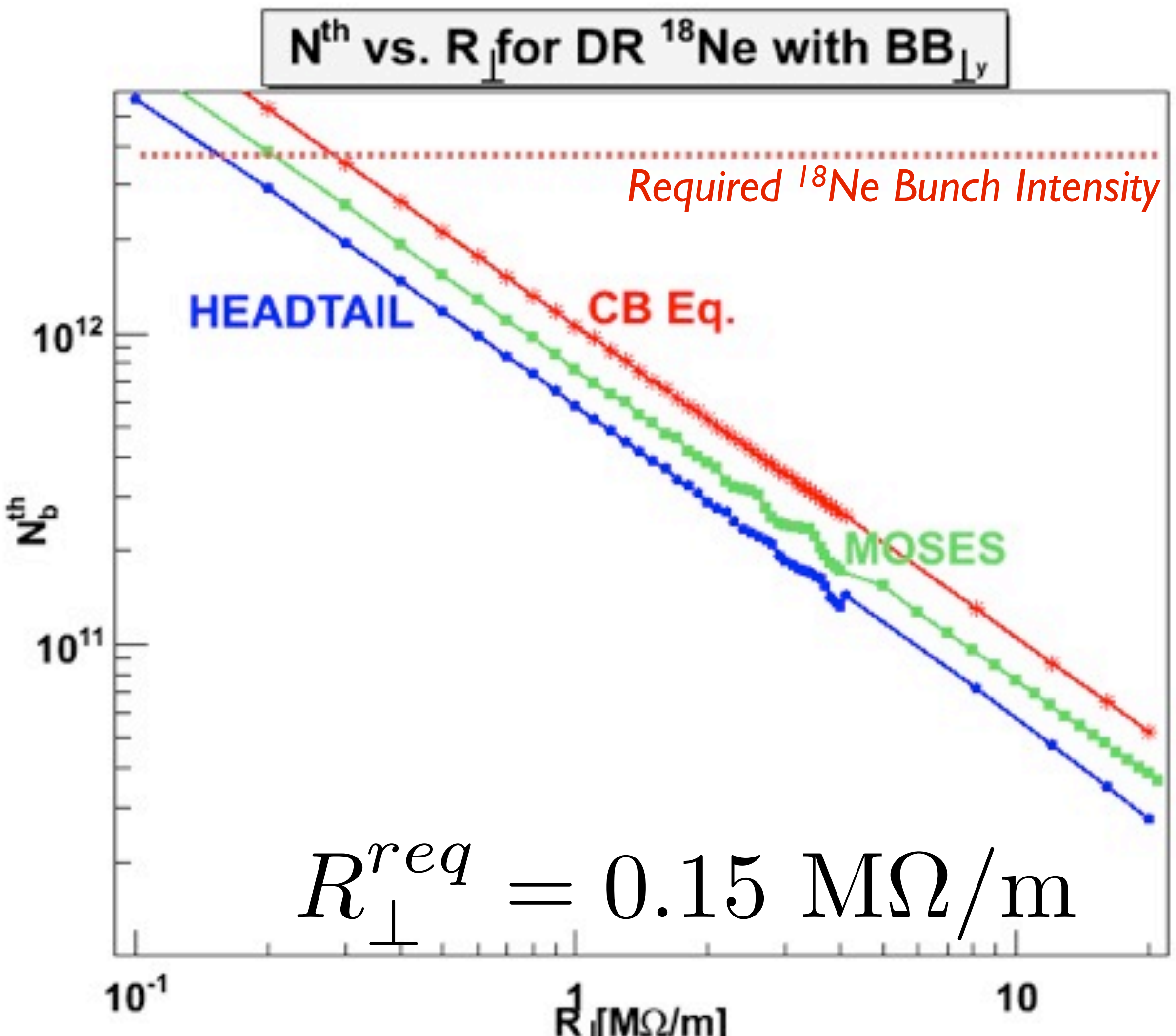

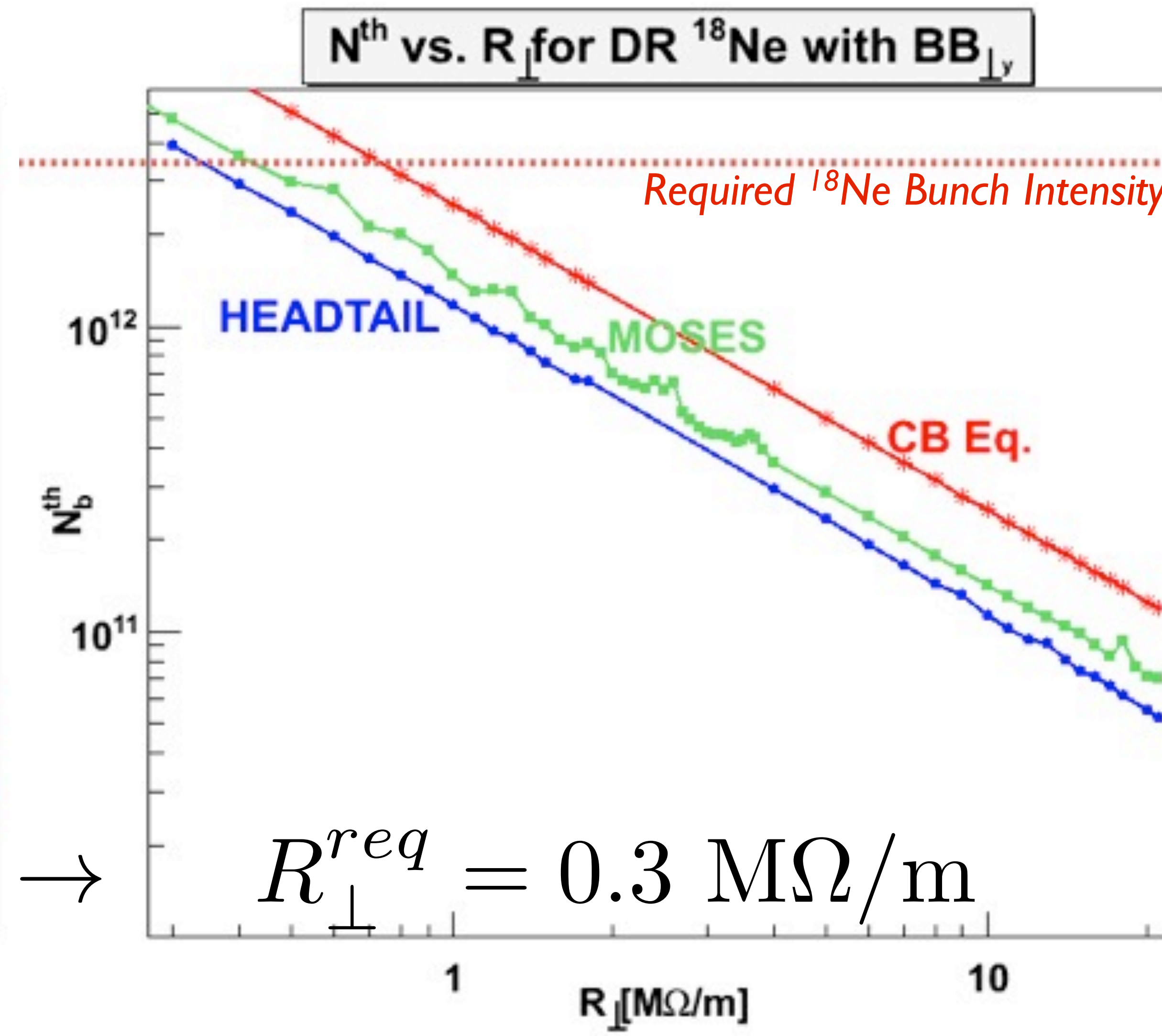

$$R_\perp^{req} = 0.15 \text{ M}\Omega/\text{m} \rightarrow R_\perp^{req} = 0.3 \text{ M}\Omega/\text{m}$$

- **So $R_\perp^{req}$ is still a factor 3.3 too small** ($R_\perp^{DR}$ ~ 1 MΩ/m)

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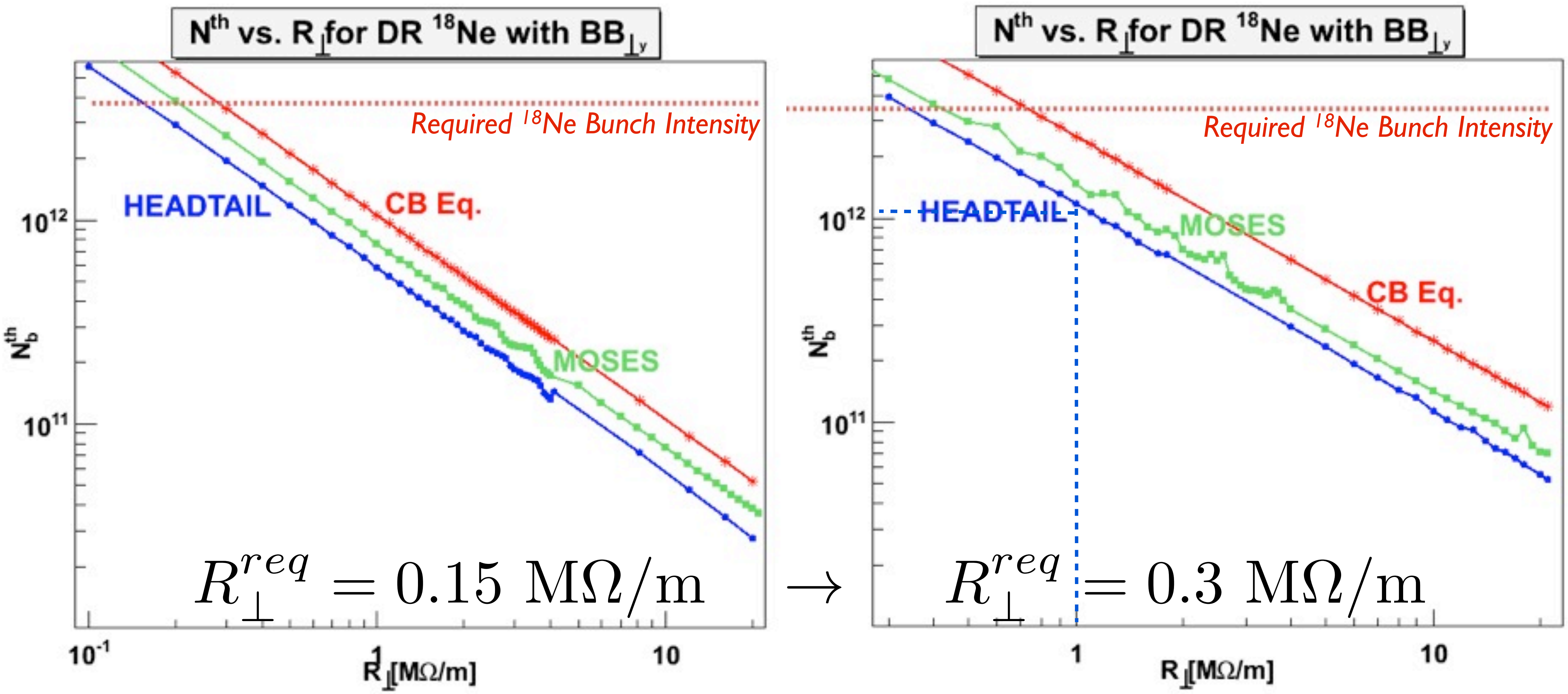

- **N_b^{th} = 12e11 ^{18}Ne can be used to get N_b^{th} for all other ions by using that CB Eq. goes as** $N^{th}_{b_{x,y}} \propto \frac{A}{Z^2}$

DR Intensity Limit for New Lattice

A L L I O N S

$R_\perp^{DR}$ = 1 MΩ/m	Bunch Intensity Limit, N_b^{th} [e12]	Bunch Intensity Limit, N_b^{th} [% of N_b^{nom}]
^{6}He	10	224
^{18}Ne	1.2	35
^{6}He	10	112
^{18}Ne	1.2	70
^{6}He	10	112
^{18}Ne	1.2	175
^{8}Li	5.9	129
^{8}B	2.1	127
^{8}Li	5.9	65
^{8}B	2.1	64
^{8}Li	5.9	26
^{8}B	2.1	25

^{8}Li	^{8}B	^{6}He
129	127	224
65	64	112
26	25	45

$$N_b^{nom} = \frac{\Phi_0 L_{circ} t_{sps}}{N_{bunches} L_{eff} T_{eff}^{year}} \left(1 - 2^{-\frac{t_{sps}}{\gamma t_{1/2}}}\right)^{-1}$$

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^{8}Li	$\bar{\Phi}_0$	5	1.5×10^{-3}	3×10^{-2}
^{8}B	Φ_0	5		
^{8}Li	$\bar{\Phi}_0 \times 2$	5	7×10^{-4}	1.5×10^{-2}
^{8}B	$\Phi_0 \times 2$	5		
^{8}Li	$\bar{\Phi}_0 \times 5$	5	2×10^{-4}	8×10^{-3}
^{8}B	$\Phi_0 \times 5$	5		
^{8}Li	$\bar{\Phi}_0$	3	1.7×10^{-3}	3×10^{-2}
^{8}B	Φ_0	5		
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^{6}He	$\bar{\Phi}_0 \times 2$	2		
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^{8}B	$\Phi_0 \times 5$	5		
^{6}He	$\bar{\Phi}_0 \times 5$	2		

Conclusions

CONCLUSION

- Transversal Broad Band Impedance enforces redesign of the Beta Beam Decay Ring
  (Other collective effects still to be studied)

- A new design of the Decay Ring (by A. Chancé)
  - ➡ Increases slip-factor, voltage and straight fraction
  - ➡ More of the Beta Beam scenarios are allowed
    (assumed $R_{\perp}^{DR}$ = 1 MΩ/m):

$R_{\perp}^{DR}$ = 1 MΩ/m	Bunch Intensity Limit, N_b^{th}	
	[e12]	[% of N_b^{nom}]
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Thank You!

Backup Slides

To Do

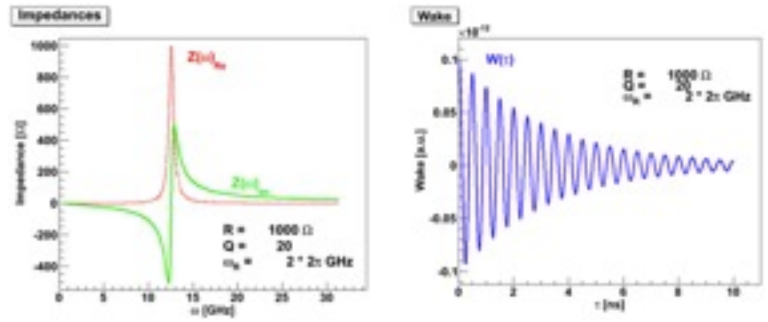
OUTLOOK

- Same study in longitudinal plane

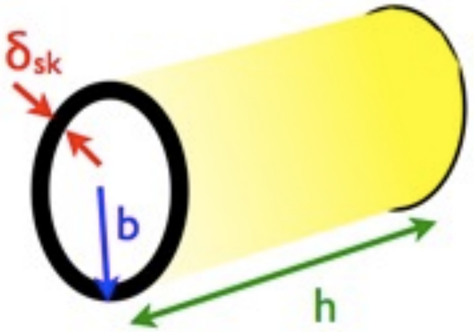
$$Z_{||}(\omega) = \frac{R_{||}}{1 + iQ\left(\frac{\omega_r}{\omega} - \frac{\omega}{\omega_r}\right)}$$

  - ➡ Ongoing HEADTAIL simulations, but can't use MOSES since only for ⊥

- Same with Narrow Band

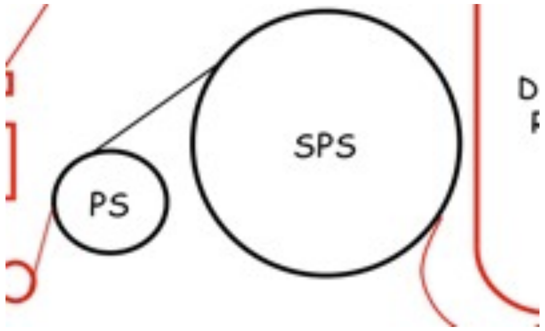


- Same with Resistive Wall Impedance



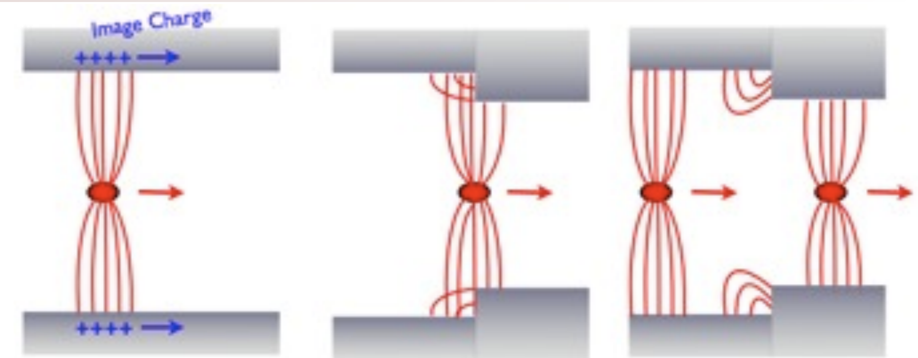
- Same with Space Charge

- Same with the already existing SPS & PS

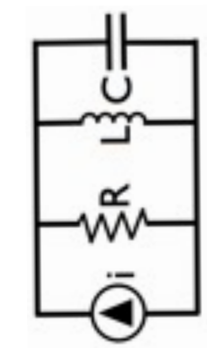


Resonance Impedance

W A K E   F I E L D S



- Wake Fields *(time domain; W(t))* can
  - be trapped in pipe cavities
  - cause "**Resonance Impedance**"

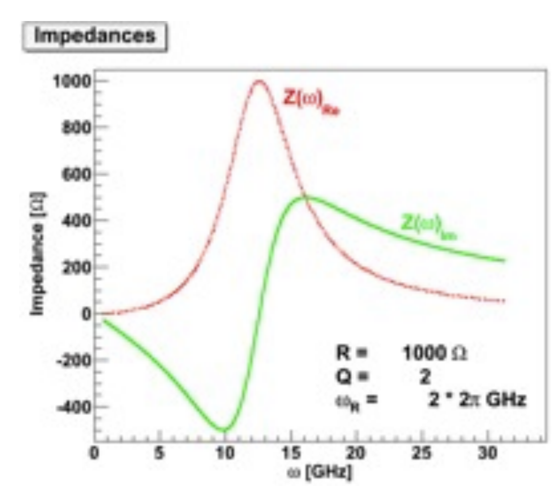


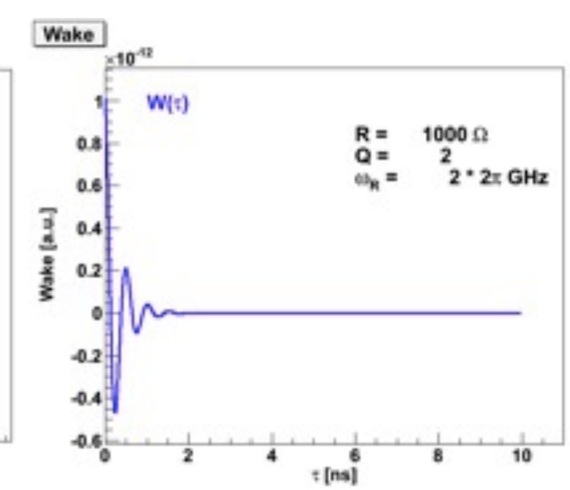
- Resonance Impedance *(frequency domain; $Z(\omega)=\mathcal{F}[W(t)]$)*,
  - in the Transverse plane can be modeled by an RLC circuit as:

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

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

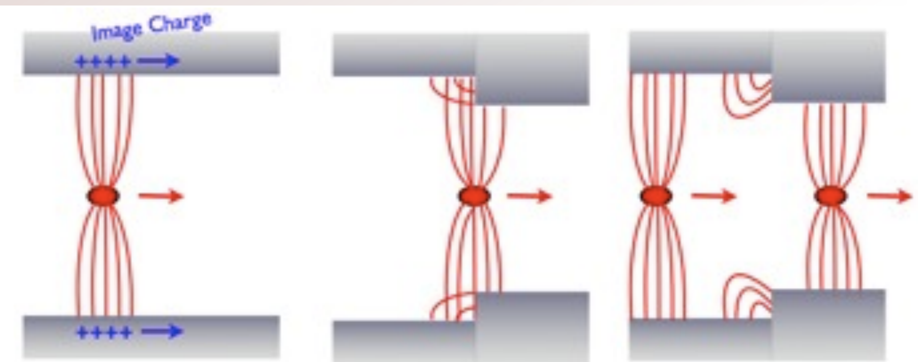
  - For low Quality Factor ($Q \approx 1$) the Wake Field is short lived and the impedance is "Broad Band"





Resonance Impedance

WAKE FIELDS



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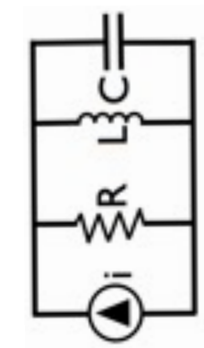

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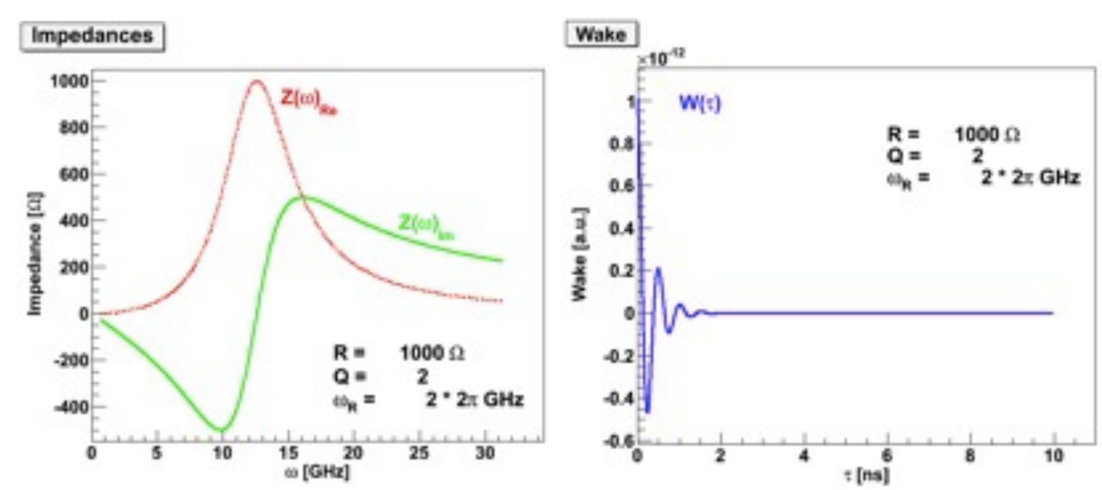
Q = **"Quality Factor"**
ω_r = **"Resonance Angular Frequency"**
$R_\perp$ = **"Shunt Impedance"**

= 1
≈ $\omega_c = \beta c/b_y$
(see next slide)

  - For low Quality Factor (Q≈1) the Wake Field is short lived and the impedance is "Broad Band"

- Will show results from

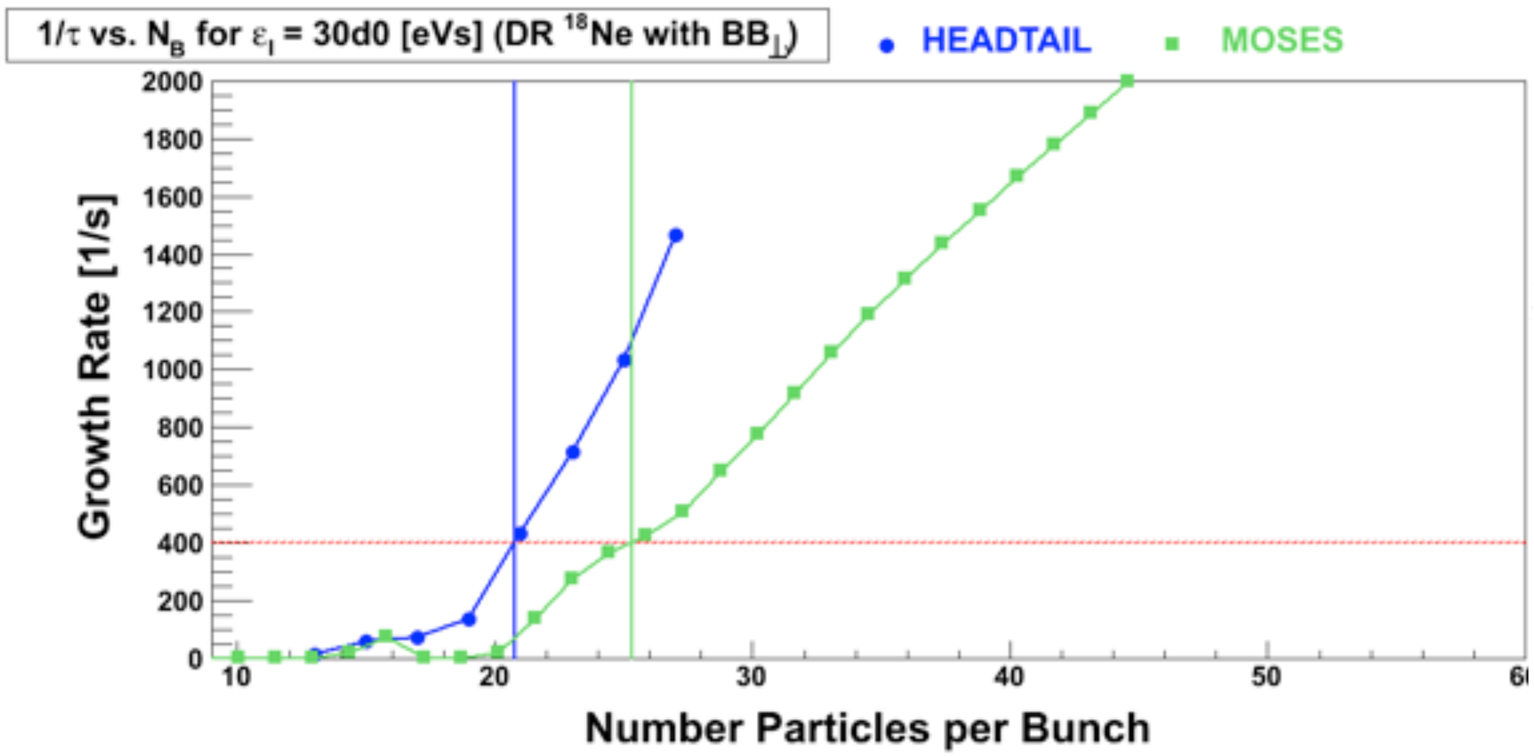
  "Transverse Resonance Broad Band Impedance"

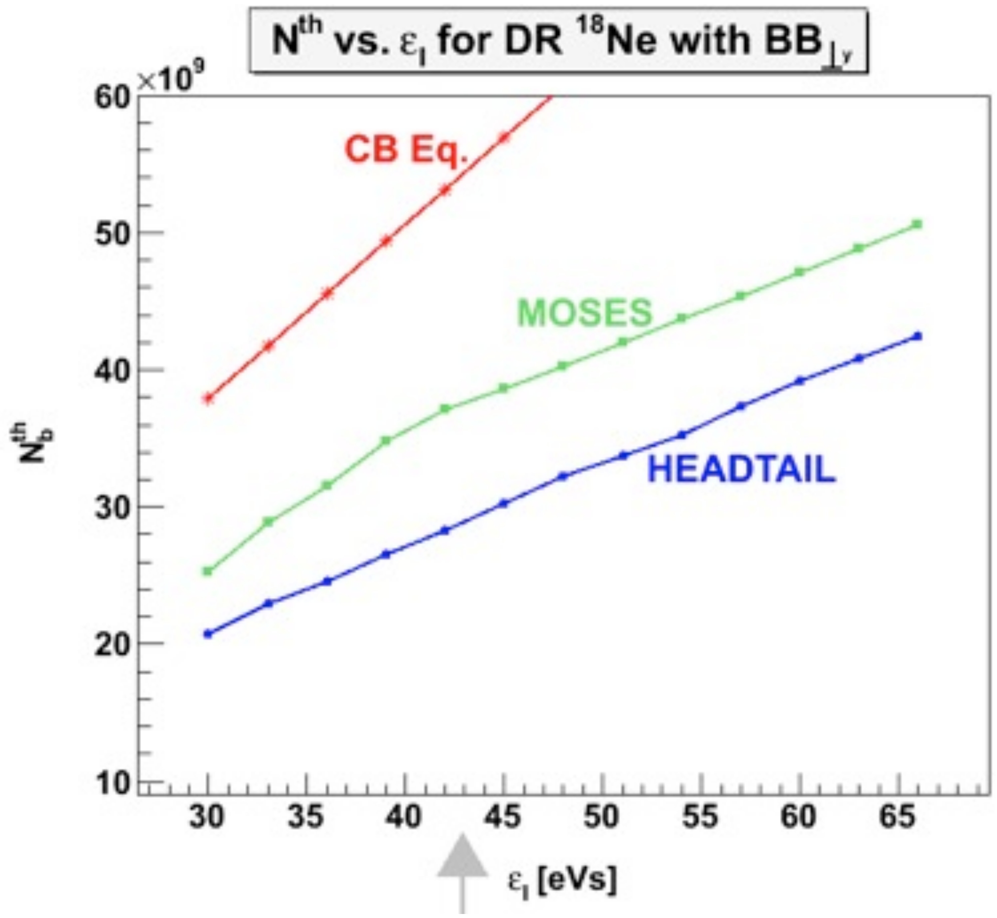


ε_l Scan for ^{18}Ne $(1/\tau)^{th}$ = 400Hz

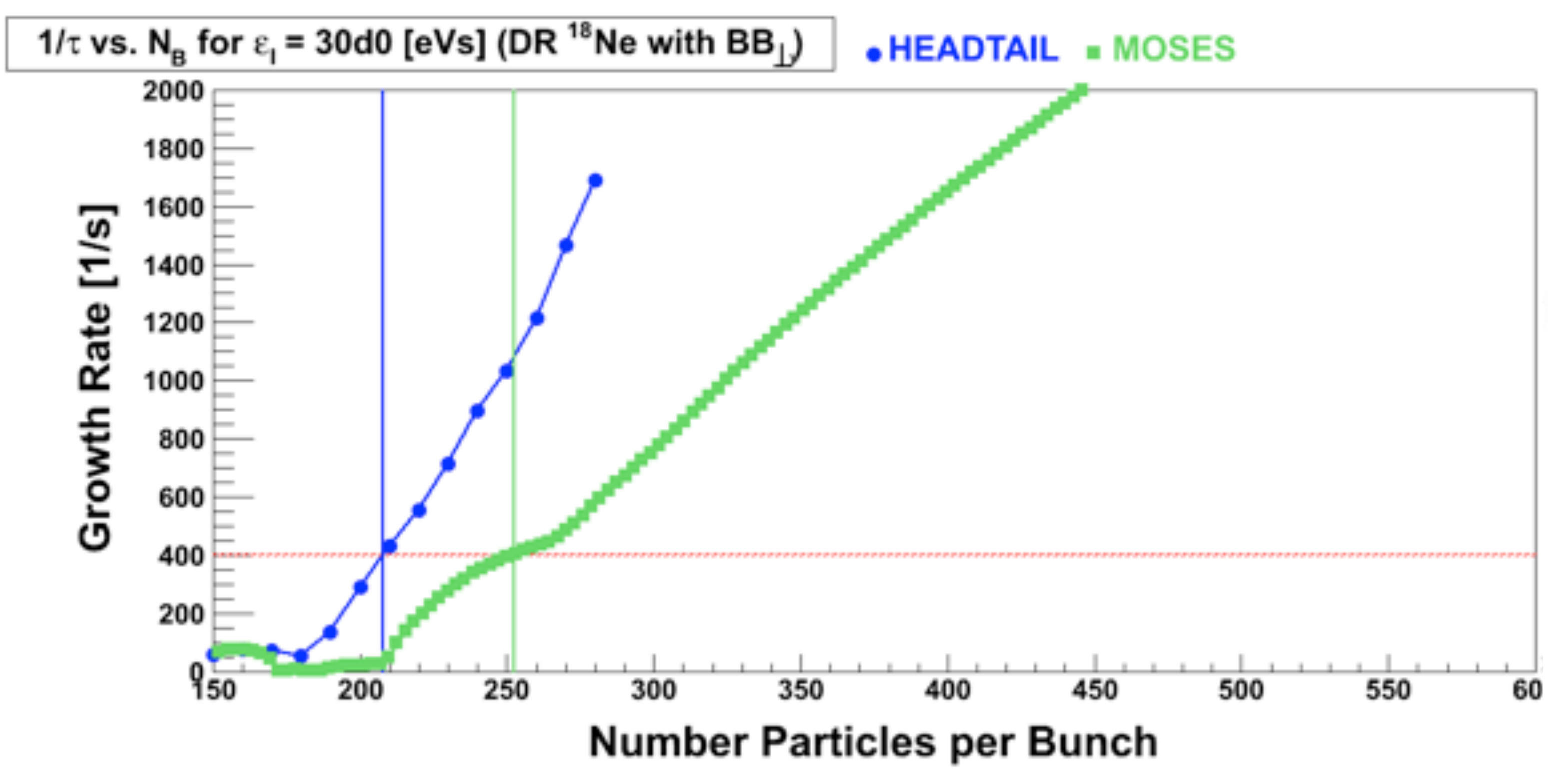
THRESHOLD

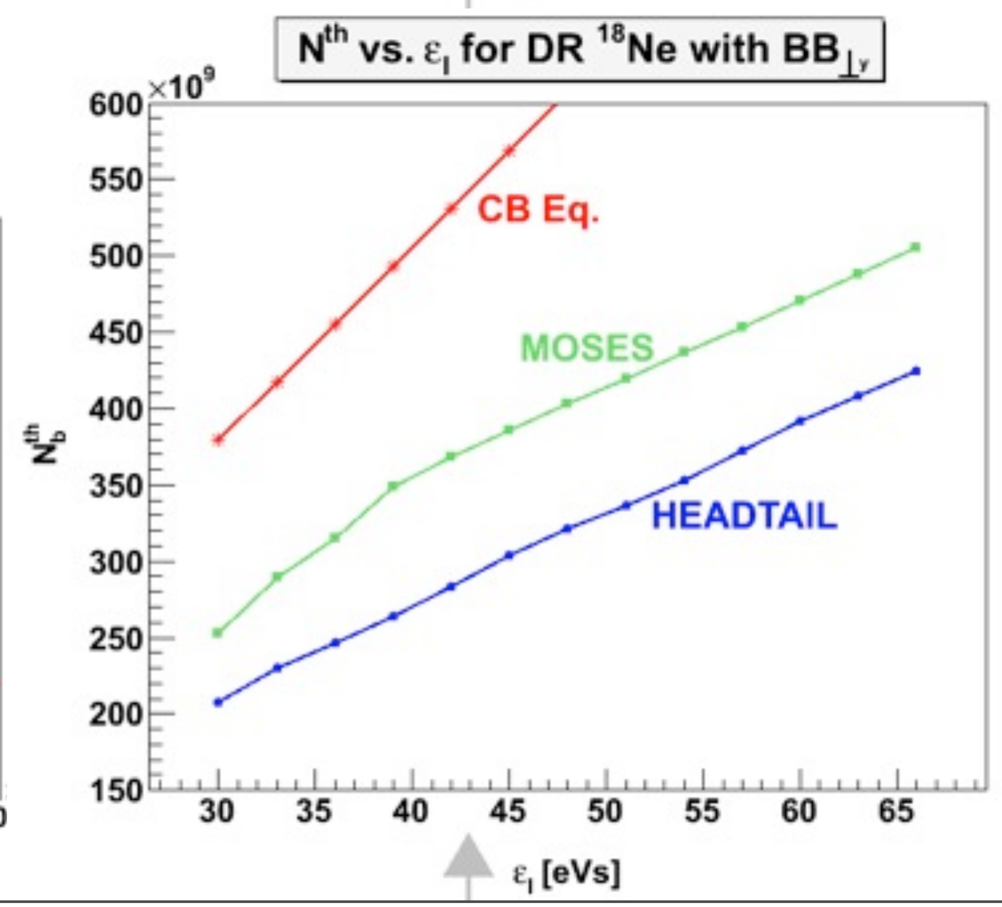
R$_\perp$ = 20 MΩ/m (SPS)





R$_\perp$ = 2 MΩ/m (RHIC)





Shunt Impedance

- The "Shunt Impedance", $R_\perp$, is the main parameter in the RLC model of the Resonance Impedance

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

- Modeling existing machines the same way we have

	PS	SPS	LHC (at top energy)	LHC (no collimators)	RHIC
$R_\perp$ [MΩ/m]	3	20	30	2	2

E. Métral

W. Fisher et. ali, Analysis of Intensity Instability Threshold at Transition in RHIC