Beta Beams,
EUROnu WP4

SEVENTH FRAMEWORK PROGRAMME

New RF Simulations for the Injection into the Beta Beam Decay Ring

A. Chancé, C. Hansen, D. Heinrich

2010/10/08

Outline

- Motivation
- Method
- Results
- Conclusion

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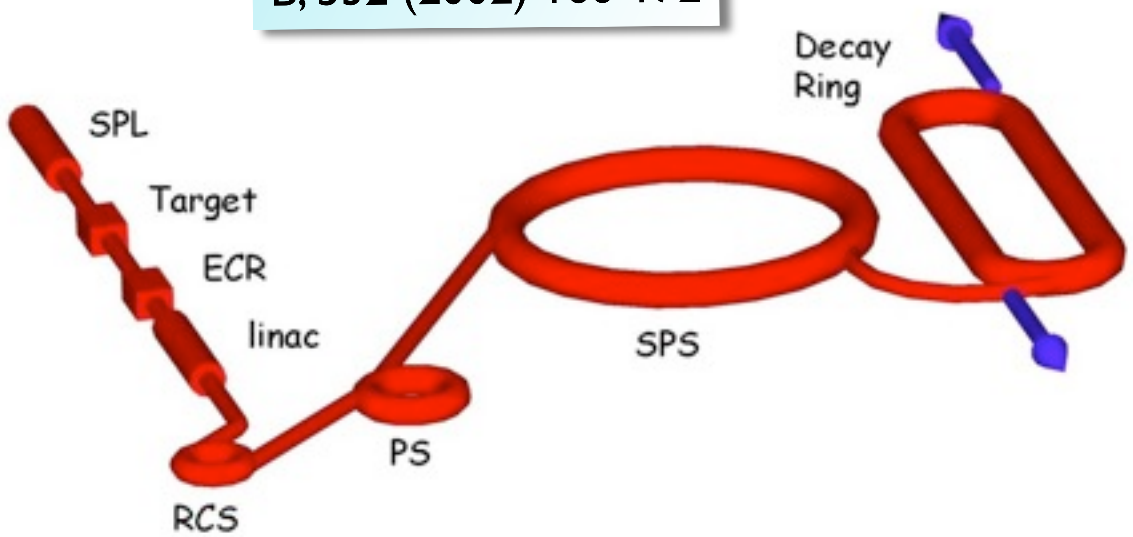
Reminder

MOTIVATION

- **To determine the three remaining neutrino oscillation parameters, θ_{13}, δ_{cp} and sign(Δm_{31}^2), precision measurements on a pure and intense neutrino beam are required**

- **One of the proposed Next Generation Neutrino Oscillation Facilities is Beta Beams:**
  - **Accelerate radioactive ions to high γ**
  - **Let them β-decay in a Decay Ring (DR) with a straight section →**
  - **ν-beam with opening angle 1/γ and with known energy and ν-species**

P. Zucchelli, Phys. Let. B, 532 (2002) 166-172



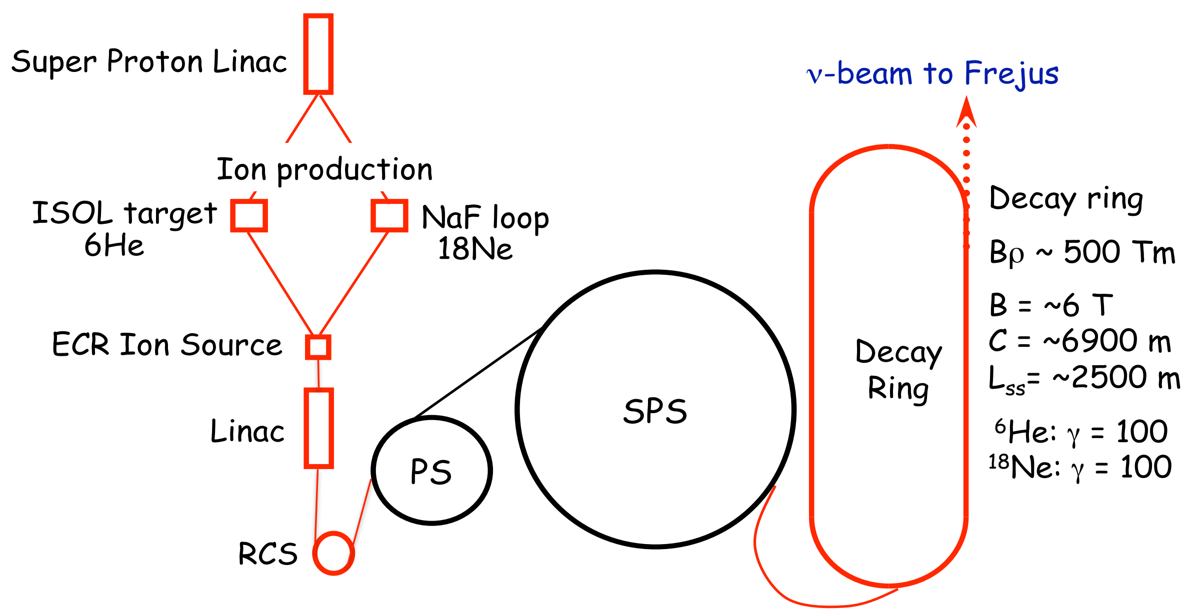
This gives only (anti) neutrinos from β^+ (β^-) decay:

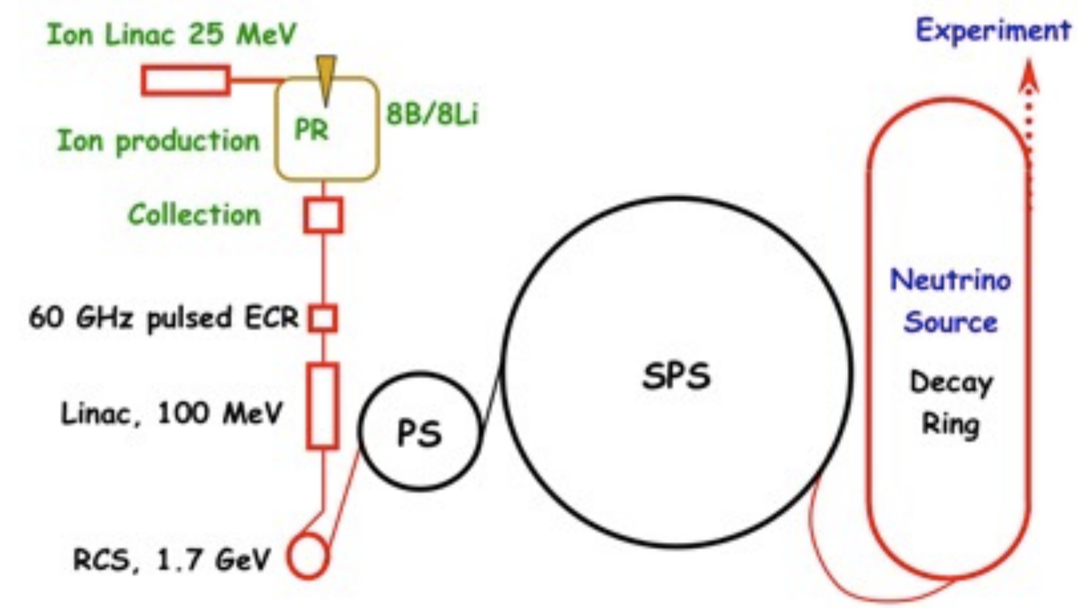
$$n \longrightarrow p + e^- + \bar{\nu}_e$$
$$\text{Signal: } \bar{\nu}_e \rightsquigarrow \bar{\nu}_\mu$$
$$p \longrightarrow n + e^+ + \nu_e$$
$$\text{Signal: } \nu_e \rightsquigarrow \nu_\mu$$

Two Baselines

MOTIVATION

- **There are currently two different baselines** (both with γ=100) **under investigation**
- **^{6}He & ^{18}Ne: L ≈ 130 km**
- **^{8}Li & ^{8}B: L ≈ 650 km**





Duty Factor

MOTIVATION

- **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, DF = filled ratio of the Decay Ring**

Duty Factor = Suppression Factor

Only "opened" when neutrinos arrive

Duty Factor

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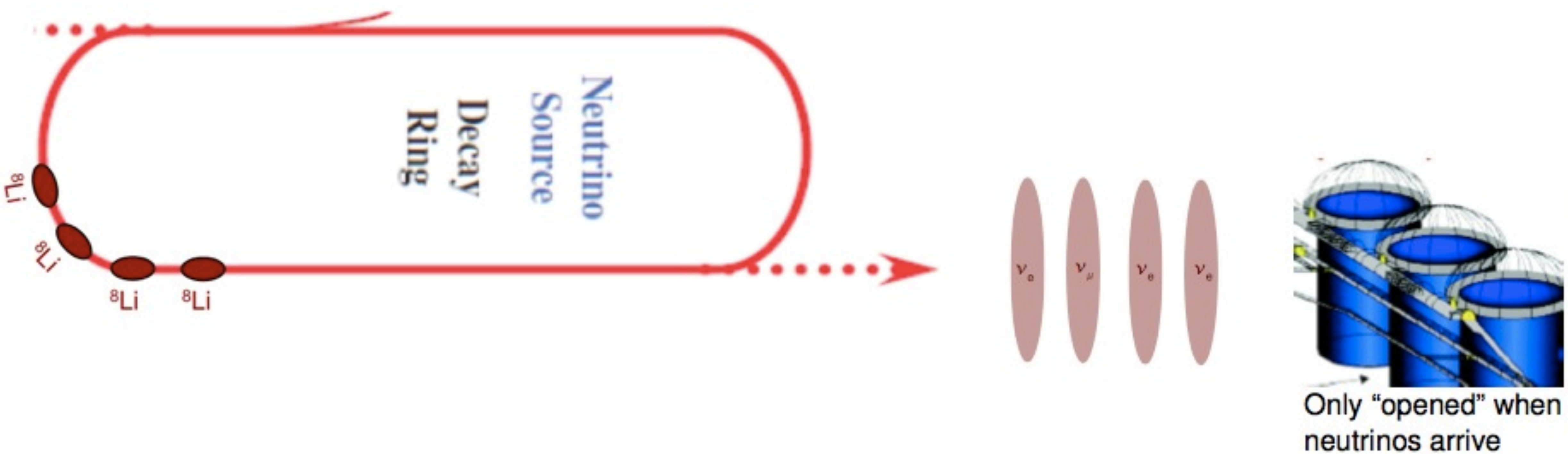
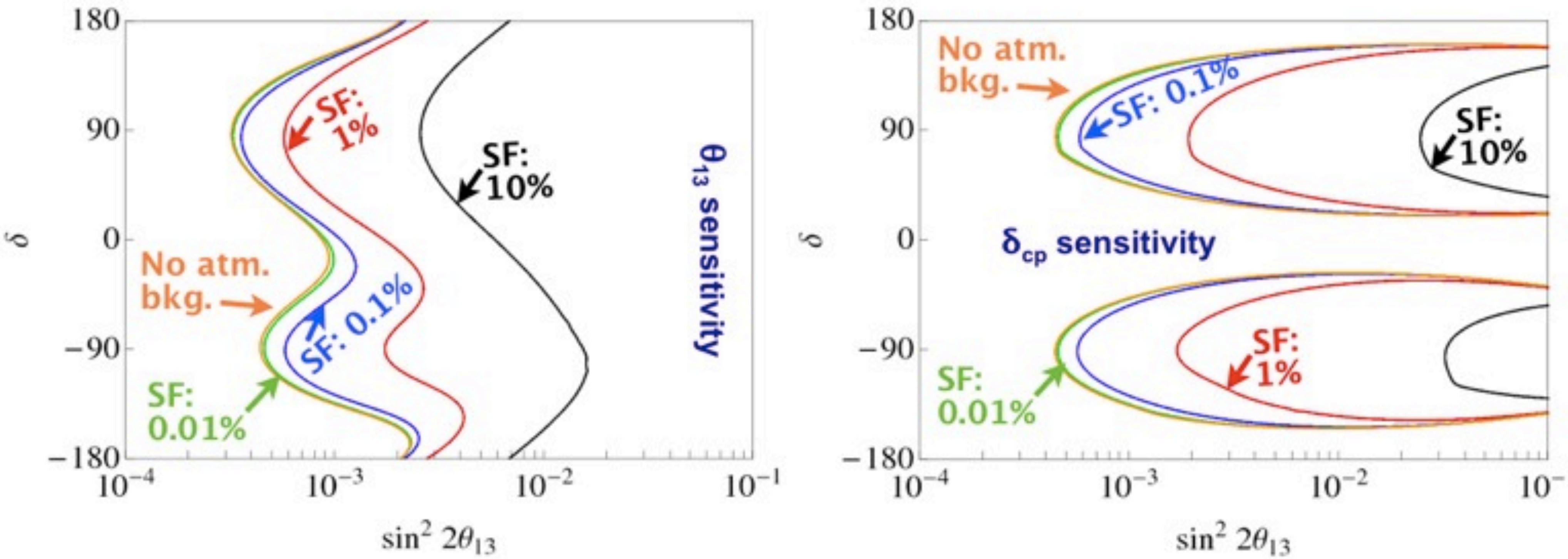


Sensitivity for ^{18}Ne & ^{6}He

- Sensitivity depends on
  - ➡ Neutrino Fluxes &
  - ➡ Suppression Factor
- Assuming the <u>*nominal flux for ^{18}Ne and ^{6}He*</u>, we get

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



E. Fernandez, The gamma = 100 Beta-Beam Revisited. Nucl. Phys., B833:96-107,2010, 0912.3804

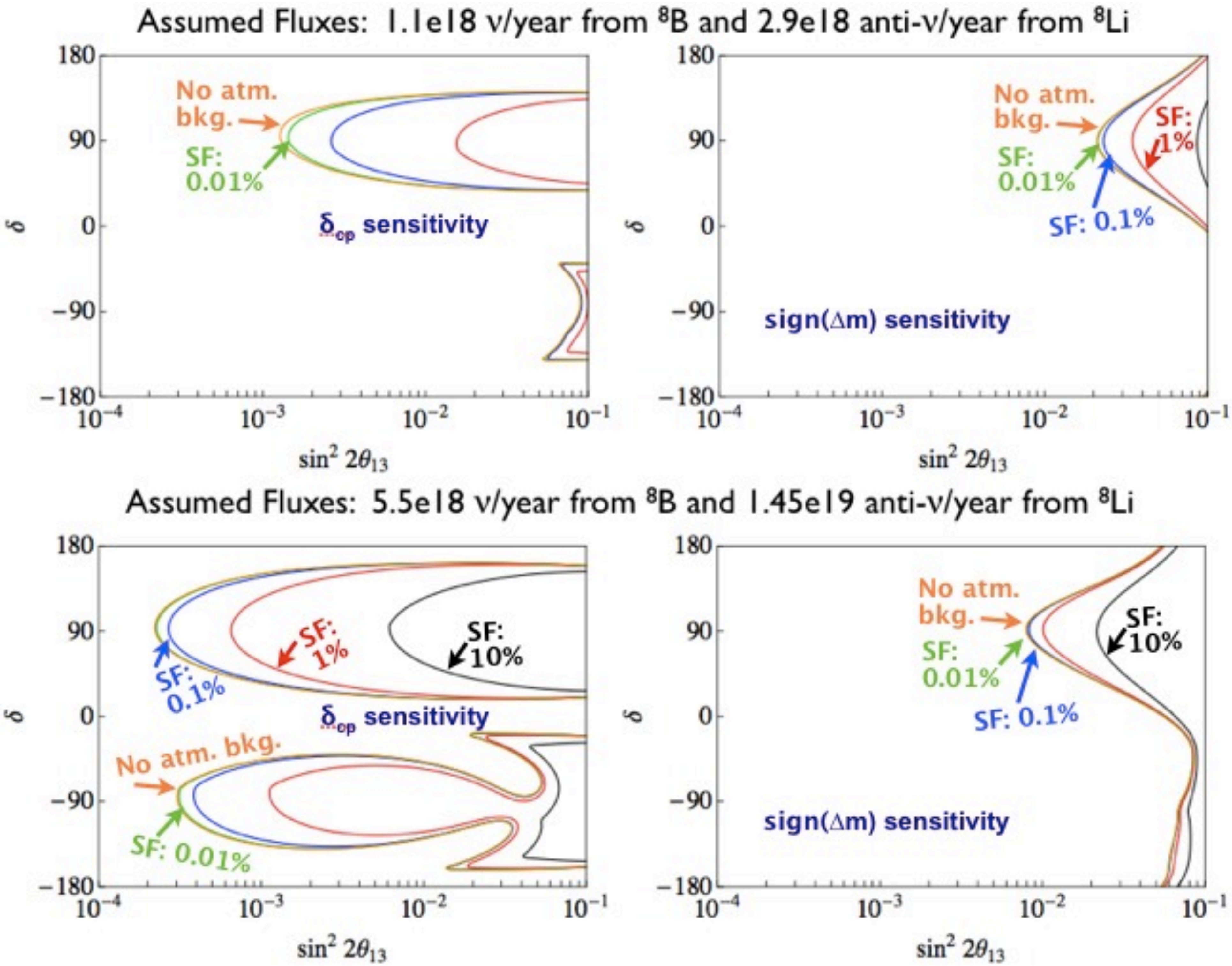
- I.e. in case of *nominal flux* we can only fill between 0.1% and 1% of the Decay Ring

Sensitivity for ^8B and ^8Li

MOTIVATION

- **Same flux as nominal flux for ^{18}Ne & ^6He** →

- **5 times the nominal flux for ^{18}Ne & ^6He** →



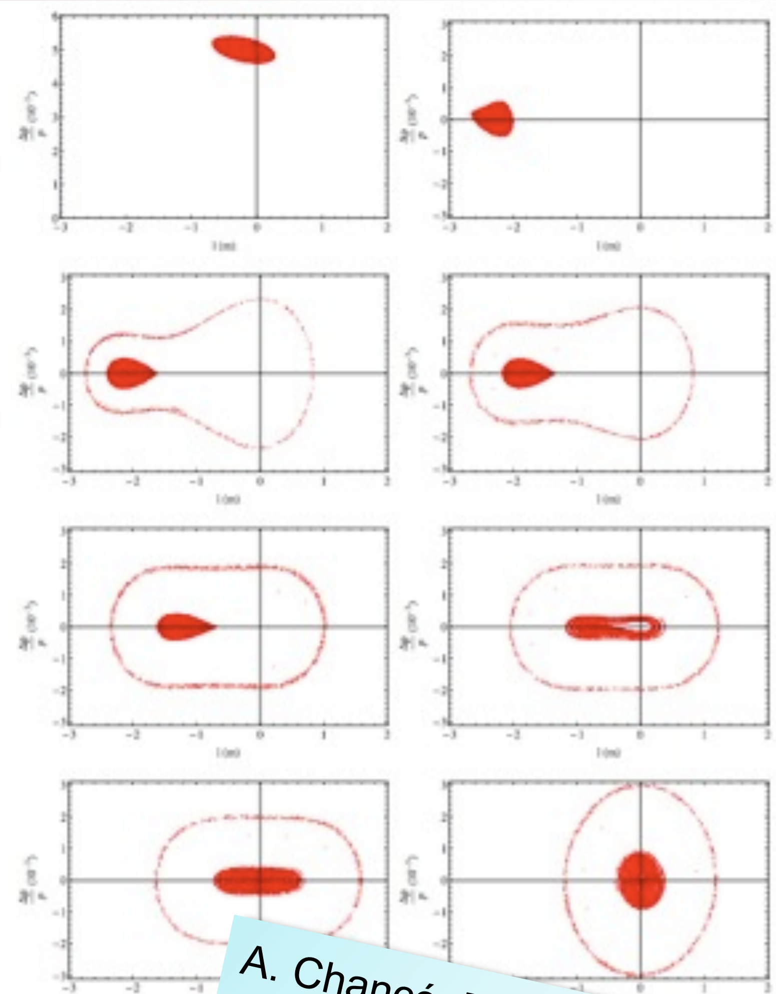
E. Fernandez, The gamma = 100 Beta-Beam Revisited. Nucl. Phys., B833:96-107,2010, 0912.3804

- I.e. ^8B and ^8Li would need a factor 5 higher flux
  (Already anticipated by A. Blondel in NUFACT07)

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

MOTIVATION

- Due to Direct Space Charge in the PS (DSC effect is worse for lower γ) ions needs to be merged in the DR to achieve enough flux
- An injection scheme was developed for ^{18}Ne & ^{6}He :
  - ➡ Off-momentum injection
  - ➡ Capture after ¼ sync. turn
  - ➡ Asymmetric and symmetric merging
  - ➡ Collimation



A. Chancé, Decay Ring Design, EURISOL Final Report

- The proportion of ions that decayed in the DR was 40% (20%) for ^{6}He (^{18}Ne)
- This scheme needed to be restudied for ^{8}B and ^{8}Li

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Work Plan

M E T H O D

- Goal:
  - ➡ Control that the merging scheme developed for ^{18}Ne & ^{6}He also works for ^{8}B & ^{8}Li
- Plan:
  - ➡ Reproduce the results for ^{18}Ne & ^{6}He
    - ✦ Use the already existing RF program →
    - ✦ Simulate with a 2D longitudinal phase space program (see next slide)
  - ➡ Repeat for ^{8}B & ^{8}Li
    - ✦ Adapt the RF program for ^{8}B & ^{8}Li →
    - ✦ Perform the 2D Simulations

A. Chancé, Decay Ring Design, EURISOL Final Report

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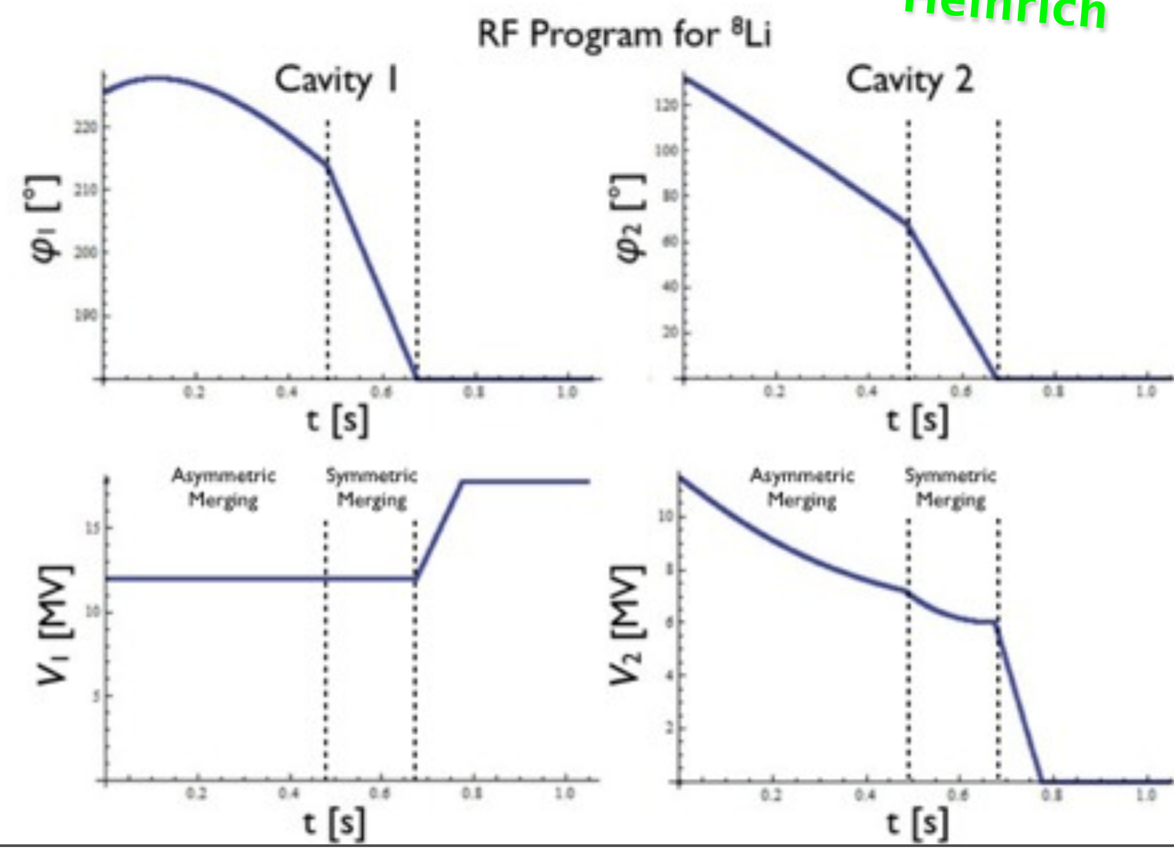
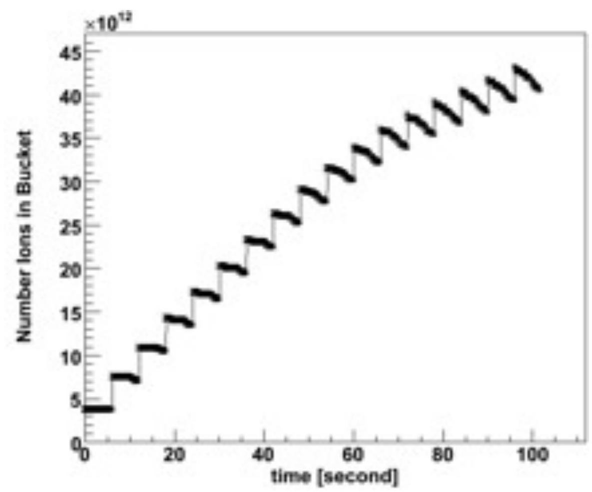


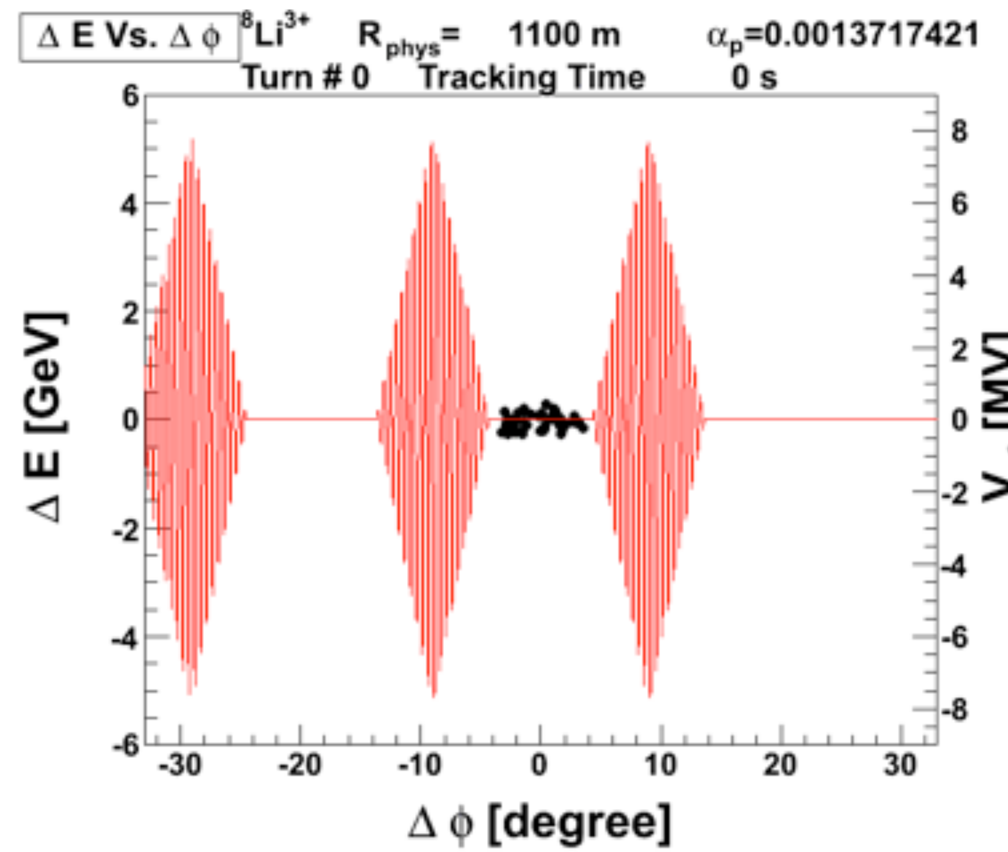
Software

M E T H O D

- The RF simulations are done with “BBPhase”
  - ➡ A 2D longitudinal phase space program
  - ➡ Originally developed to investigate the possibility to use Barrier Buckets in the DR

C. Hansen et ali, Limitations in the use of Barrier BUckets in a Beta Beam Decay RIng, AIP Conference Proceedings, 1222(1):455, 2010





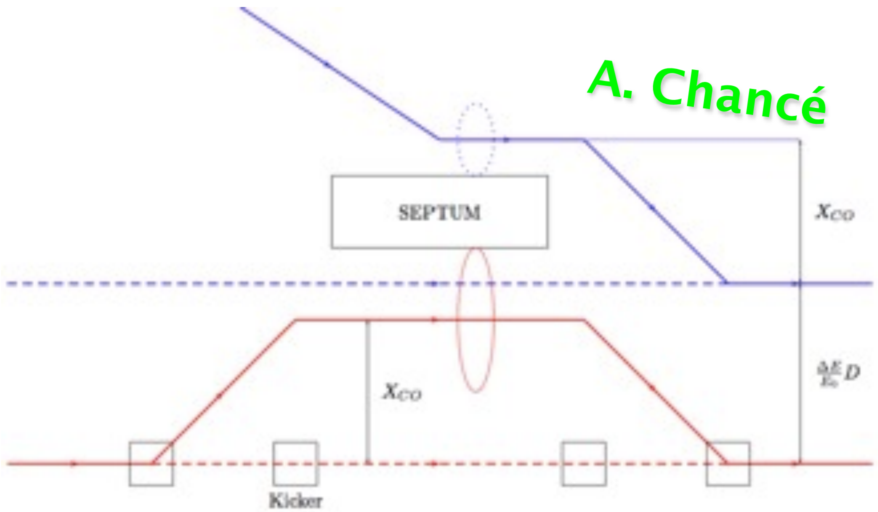
  - ➡ Now adapted to allow bunch merging simulations

SVN: http://svnweb.cern.ch/world/wsvn/bbphase

Injection

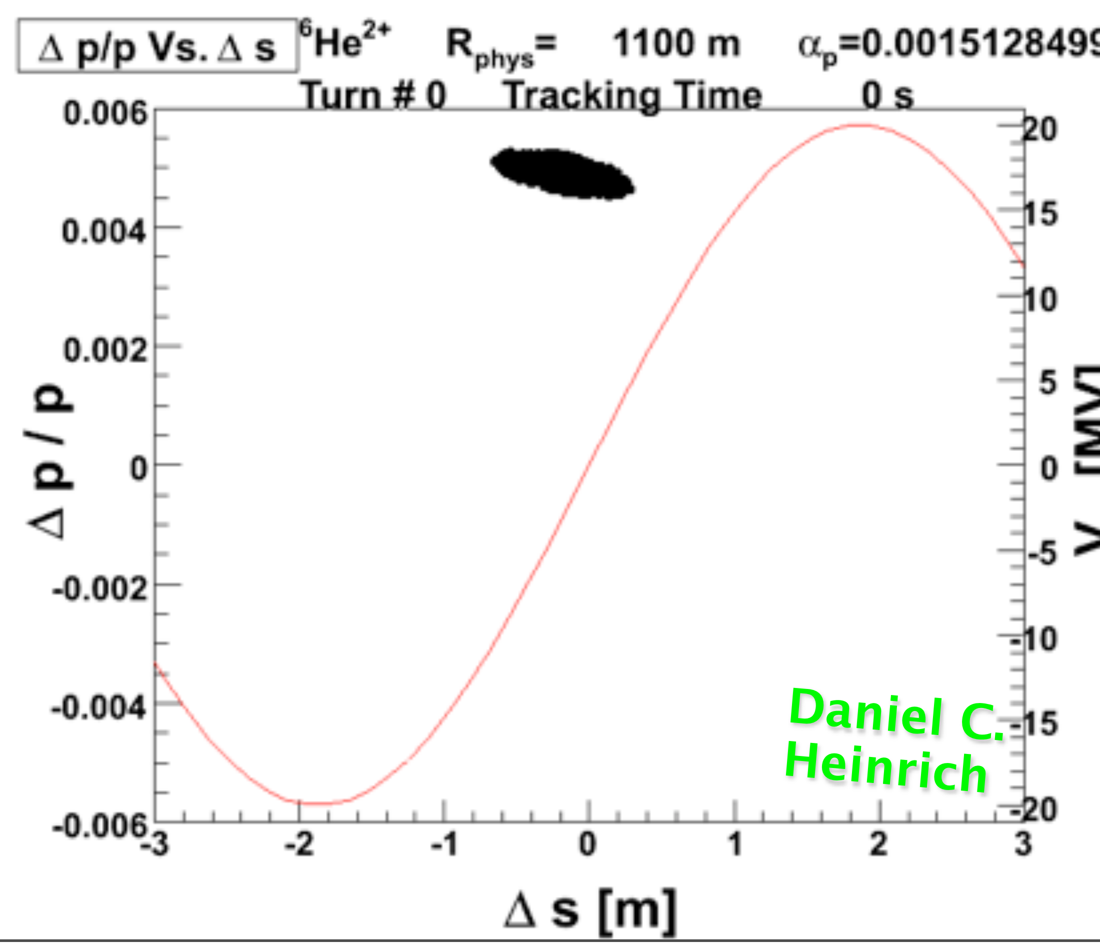
METHOD

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



- **For now: Injected bunch is elliptical with homogeneous distribution**
  (to do: implement gaussian distr.)

- **Capture efficiency optimized for injection at**
  - ➡ **δ = 4.92 ‰ $\Delta\varphi$ = 0.005°**



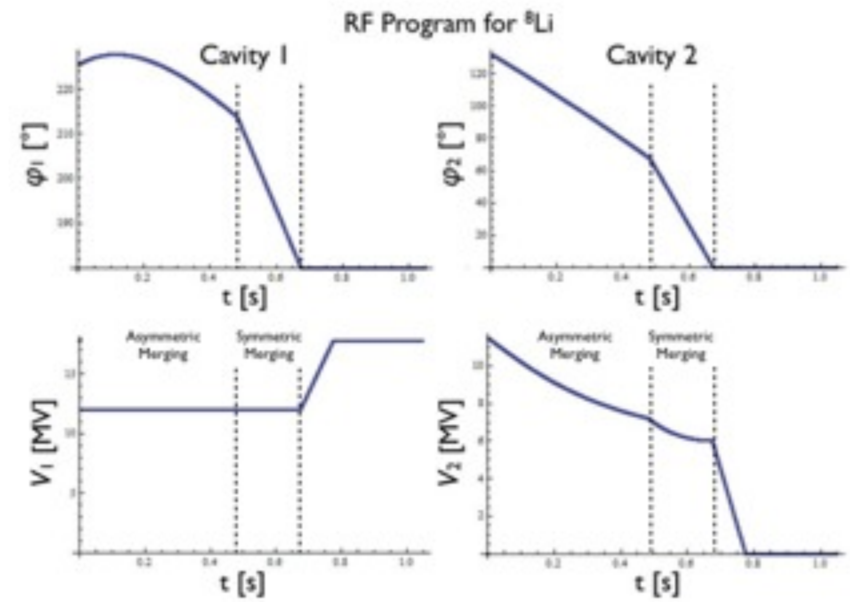
- **After ¼ synchrotron turn it is "captured" by one RF system**

- **Achieved Capture Efficiencies**
  (could be improved with gaussian distr.)
  - ➡ **88.8% for ^{6}He & 87.8% for ^{18}Ne**
  - ➡ **88.2% for ^{8}Li & 89.0 % for ^{8}B**

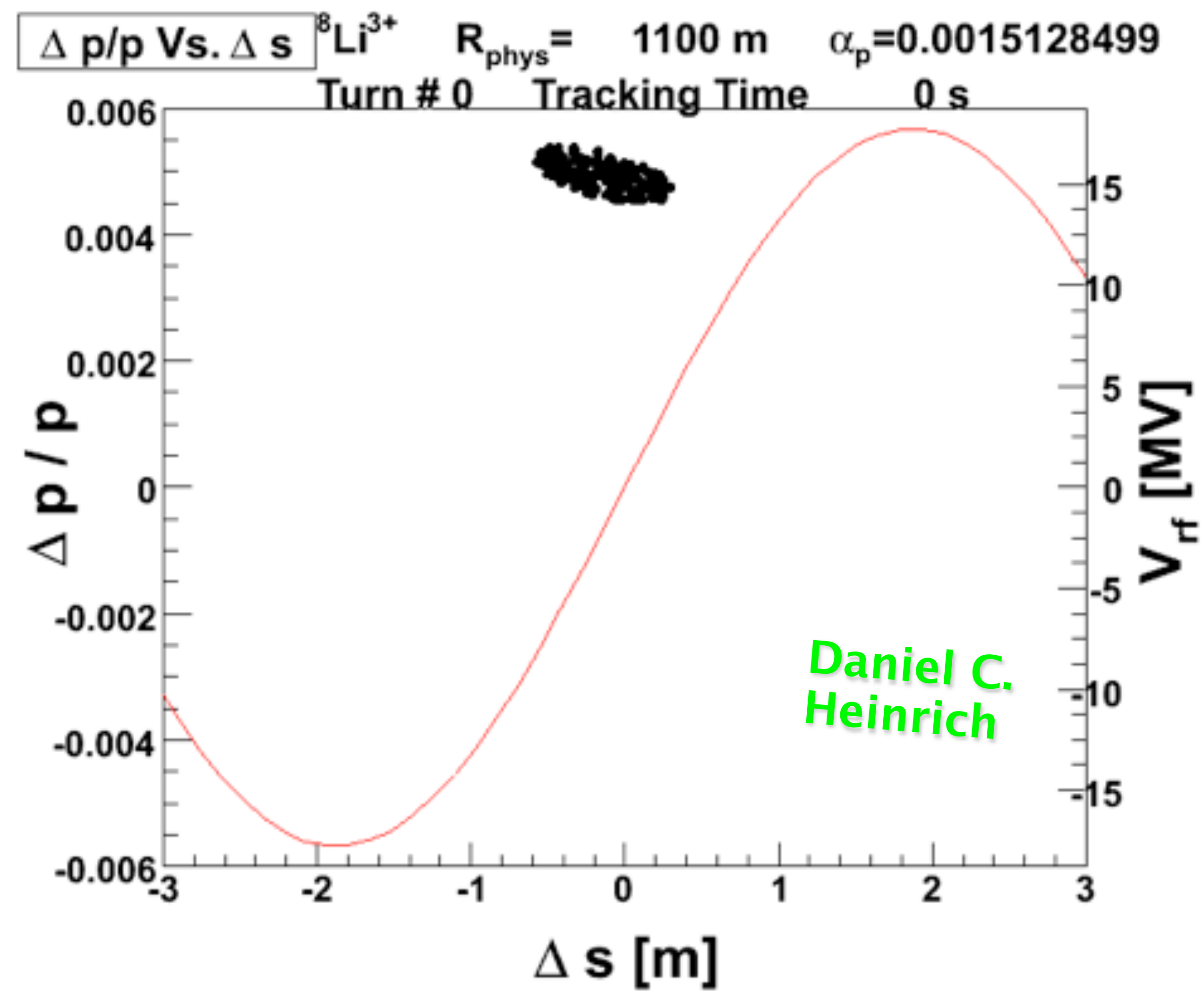
Merging & Collimation

METHOD

- Then a 2nd RF system is turned on to merge the new bunch into the old bunch
- The RF program is followed
  - ➡ **First Asymmetric Merging:** i.e. the two buckets have different size
  - ➡ **Then Symmetric Merging:** i.e. same size of the buckets



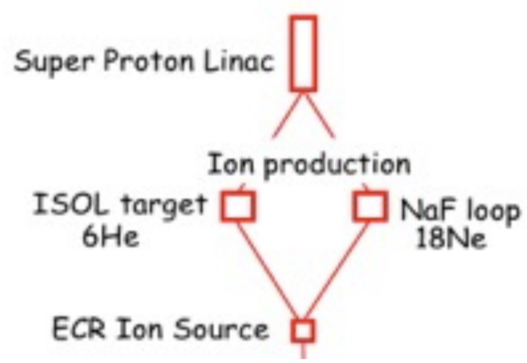
- Collimation at Δp/p = 2.5‰
  - ➡ scrapes away ions not captured
  - ➡ limits the bunch size to protect the septum magnet

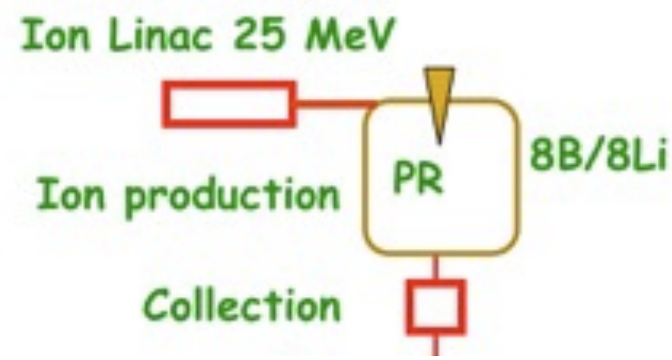


Source Rate & Injection Intensity

M E T H O D

- **Assume optimistic Ion Production Rate for both Baselines**
  - ➡ **Gives the following number ions per bunch at injection into the Decay Ring (**according to a Mathematica programs that calculates the whole Beta Beam chain)





	^{18}Ne	^{6}He	^{8}B	^{8}Li
***Assumed* Source Rate [10^{13} ions/s]**	2.1	2.0	9.0	9.0
Production Method	NaF loop	ISOL	Production Ring	Production Ring
DR Injection [10^{11} ions/ bunch]	2.35	4.87	8.43	21.50

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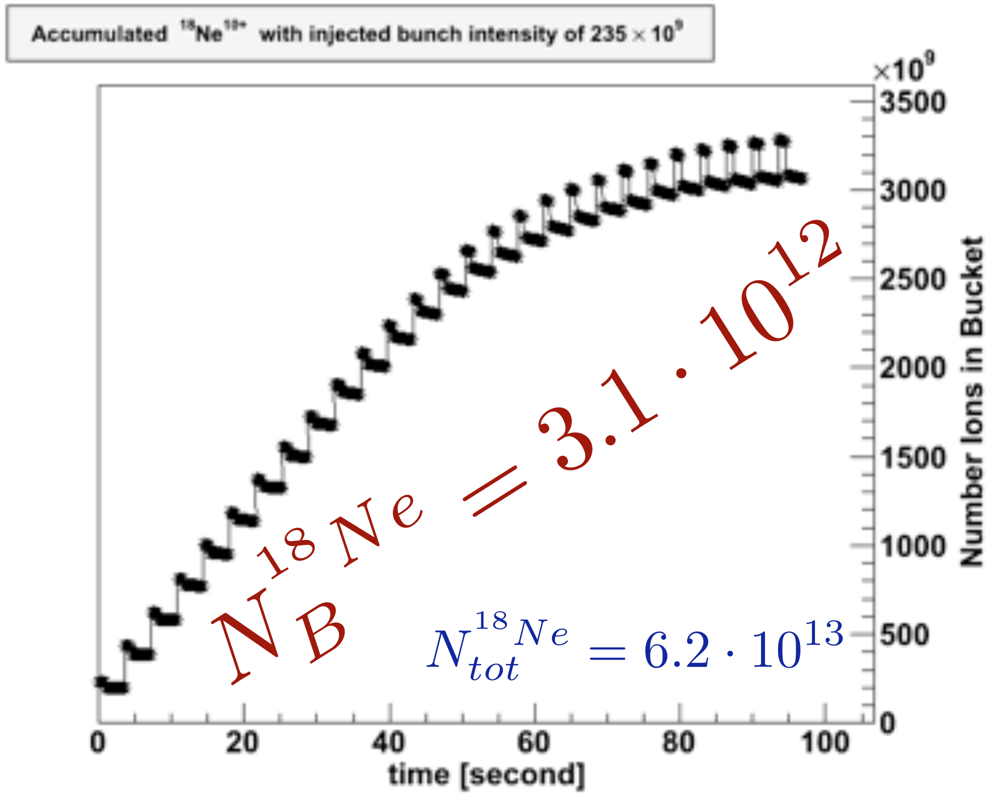
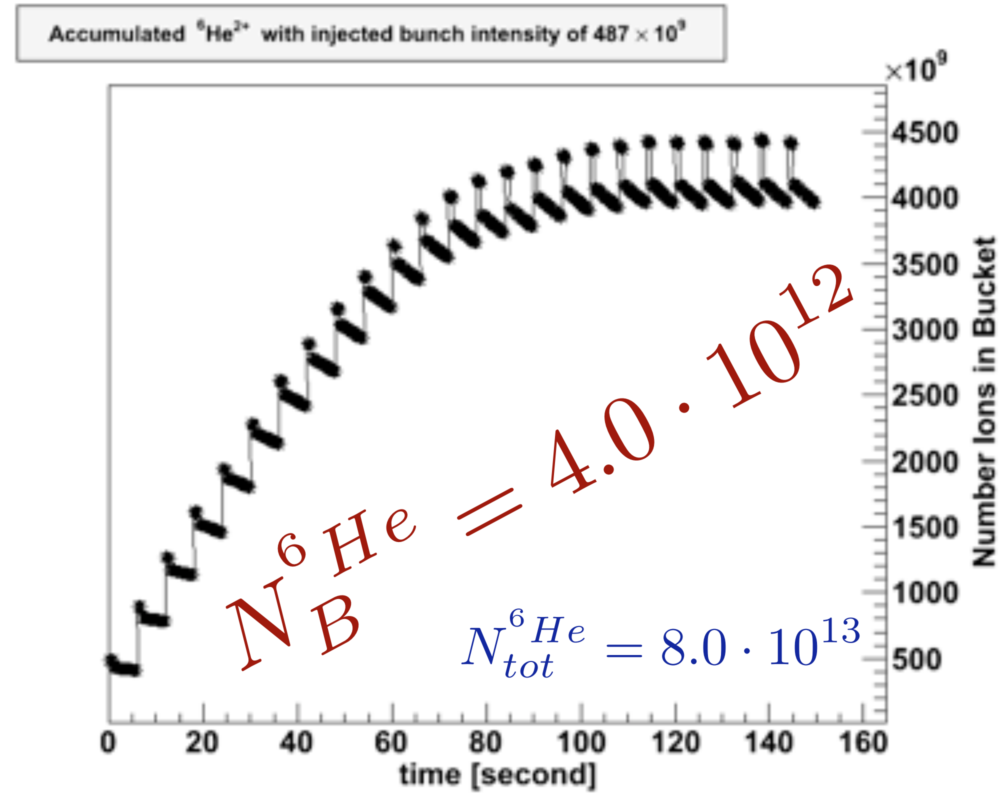
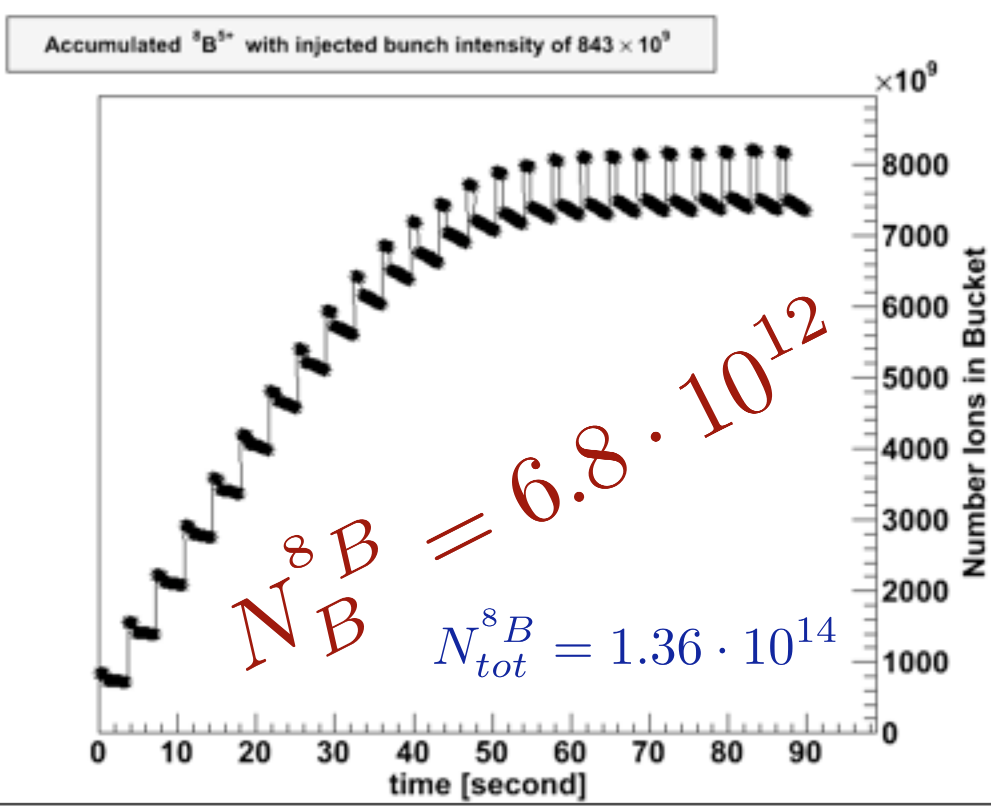
Accumulation

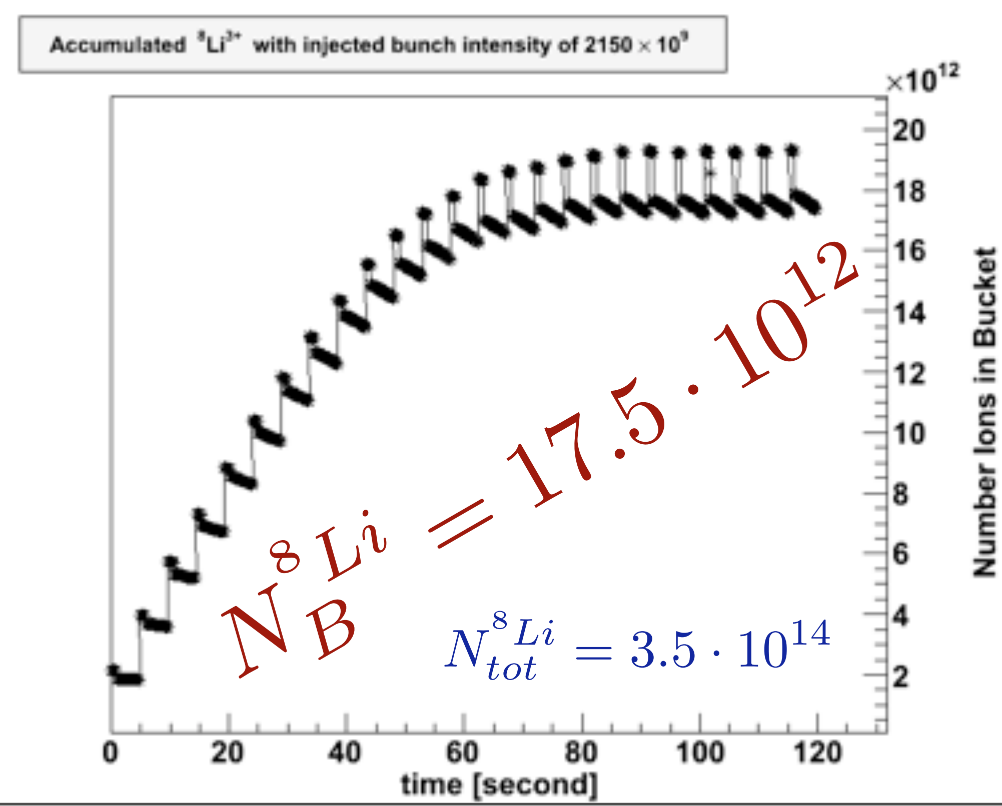
RESULTS

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









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Bunch Length

RESULTS

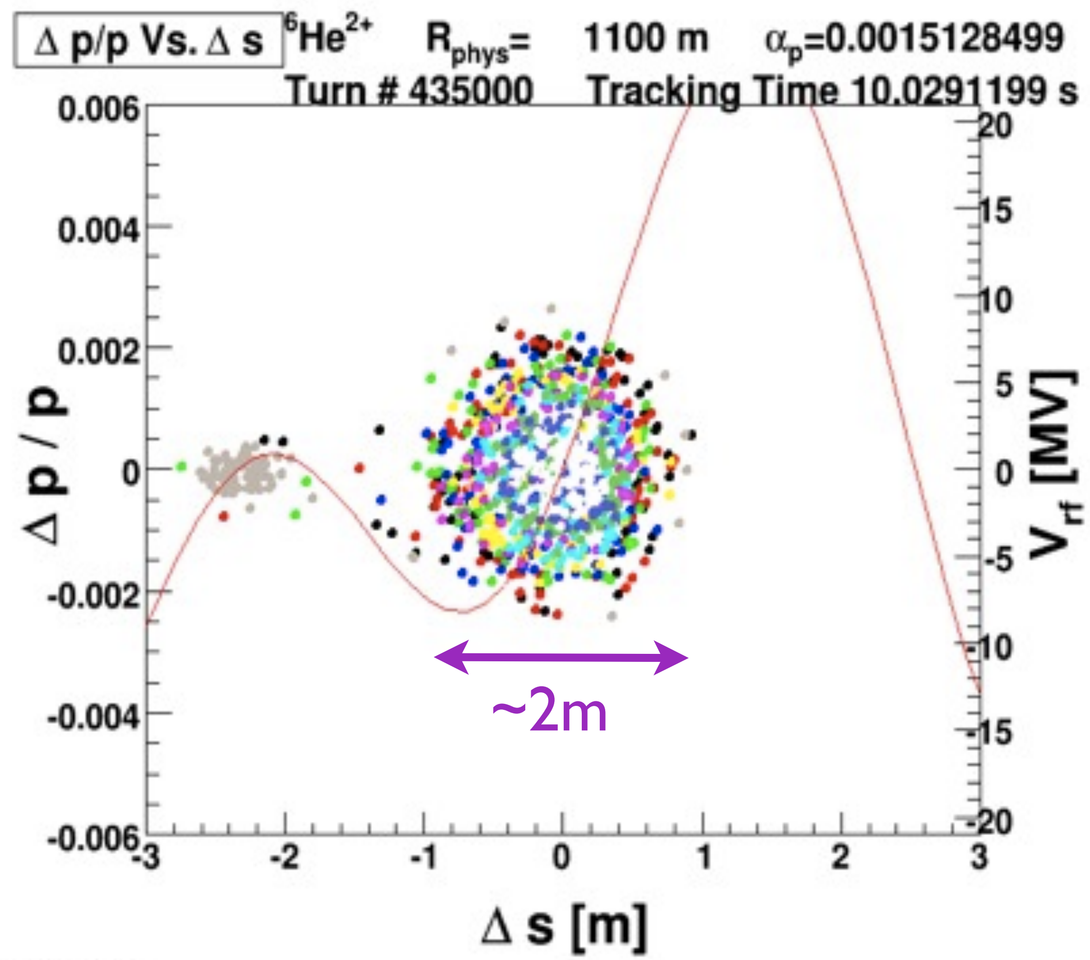
- After "saturation" the bunches are ~ 2m long (all ions)

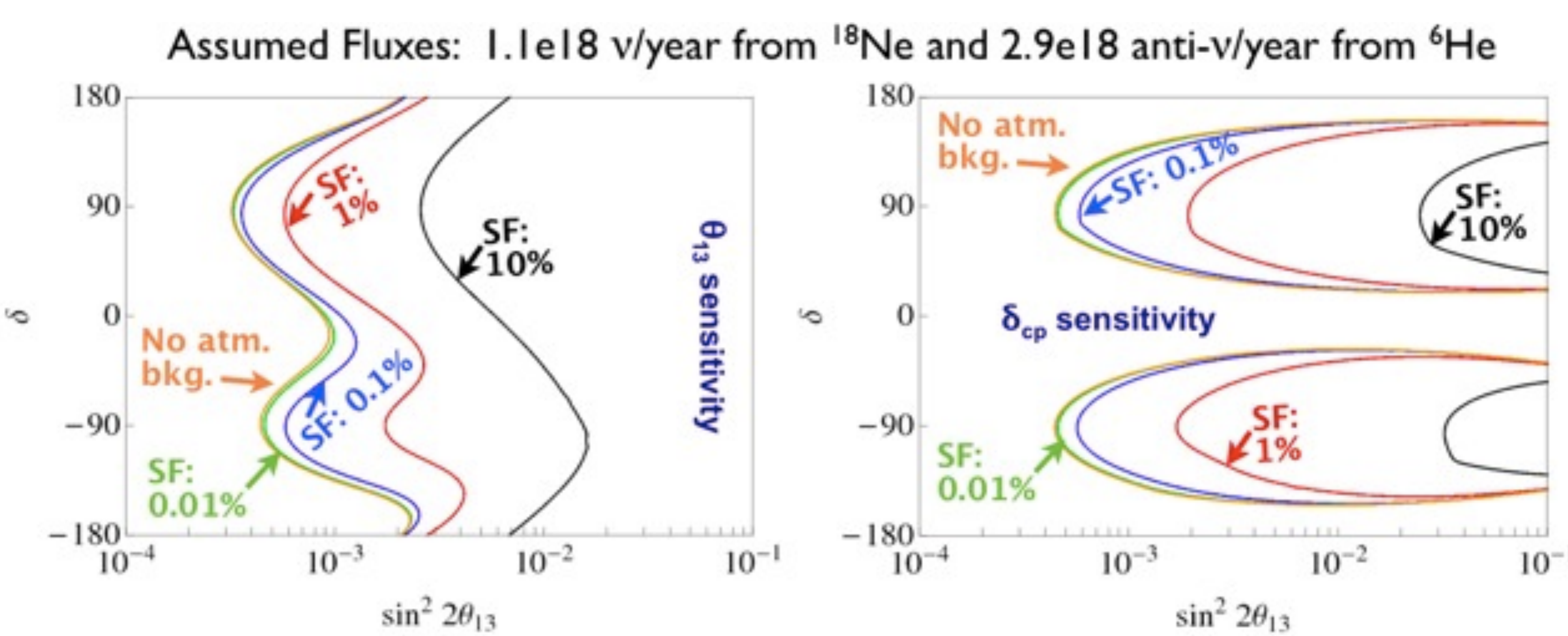
- 20 bunches from SPS to DR

  → **SF = 20 · 2m / 6911m = 0.58%**

- I.e. between 0.1% and 1%

- Good! Since for nominal:





Neutrino Flux

RESULTS

- So the simulation gave us accumulated number ions per bunch
- 20 bunches in DR → Gives the annual neutrino rate
- Assuming nominal ν flux for ^{8}B & ^{8}Li is 5 times that for ^{18}Ne & ^{6}He → Gives the "ν-flux-ratio"

	^{18}Ne	^{6}He	^{8}B	^{8}Li
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DR Injection [10^{11} ions/ bunch]	2.35	4.87	8.43	21.50

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DR Accum. [10^{12} ions/ bunch]	3.1	4.0	6.8	17.5

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ν-rate [10^{18} ν/year]	0.92	2.40	4.34	10.20

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ν-rate [10^{18} ν/year]	0.92	2.40	4.34	10.20
ν-flux-ratio	0.84	0.83	0.79	0.70

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Conclusion

- It was possible to
  - ➡ adapt the RF bunch merging scheme to the 2D program BBPhase
  - ➡ recreate the capture efficiencies for ^{18}Ne & ^{6}He achieved in "FP6"
- These results were extended to ^{8}B & ^{8}Li, however using very preliminary values for
  - ➡ ion production rate
  - ➡ emittance of injected bunches
- Bunch lengths of 2 m gives a duty factor (assuming 20 bunches) well below the upper limit of 1%

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

Backup Slides

Parameters

- So far all studies based on EURISOL FP6 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
$R_{s,\perp}$ [MΩ/m]	*Transverse Shunt Impedance*	20.00	20.00

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

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
$Q_s = \sqrt{\frac{hZeV\|\eta\cos\phi_s\|}{2\pi\beta^2 E_{tot}}}$	*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