Beta Beams,
EUROnu WP4

SEVENTH FRAMEWORK
PROGRAMME

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Status of the Production Ring for Beta Beams Studies

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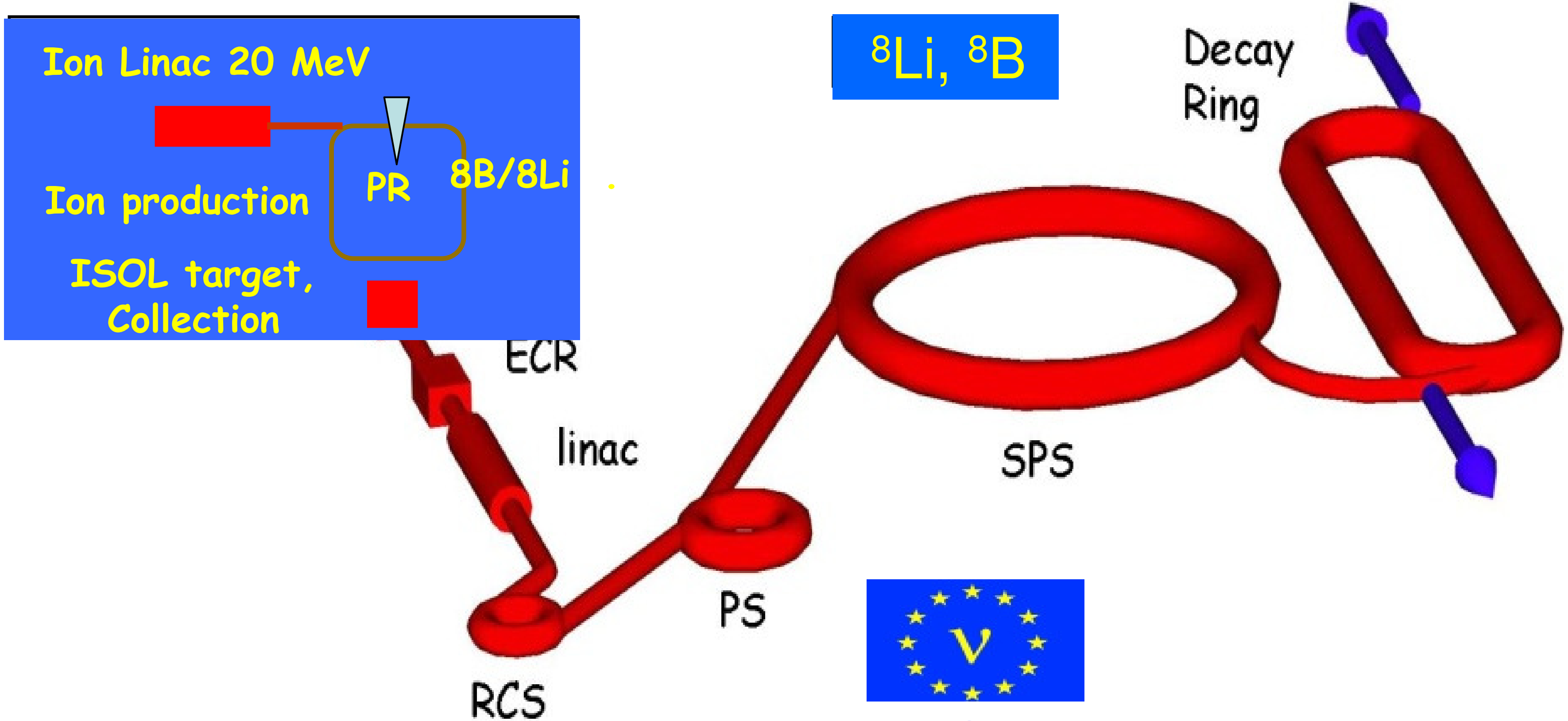
Outline

- Introduction
  - Beta-beams and the Production Ring idea
  - Ionization cooling
  - Preliminary lattice design
- Tracking simulations
- Technological challenges
- Next steps

Please refer to my presentation at the WP4 Meeting in Paris (19/2/10):
https://espace.cern.ch/betanu/MeetingsWP4/WP4Meeting4/EB_wp4Paris190210.pdf

β beams

- Aim: production of electron (anti-)neutrino beams from the β decay of radioactive ions circulating in a storage ring

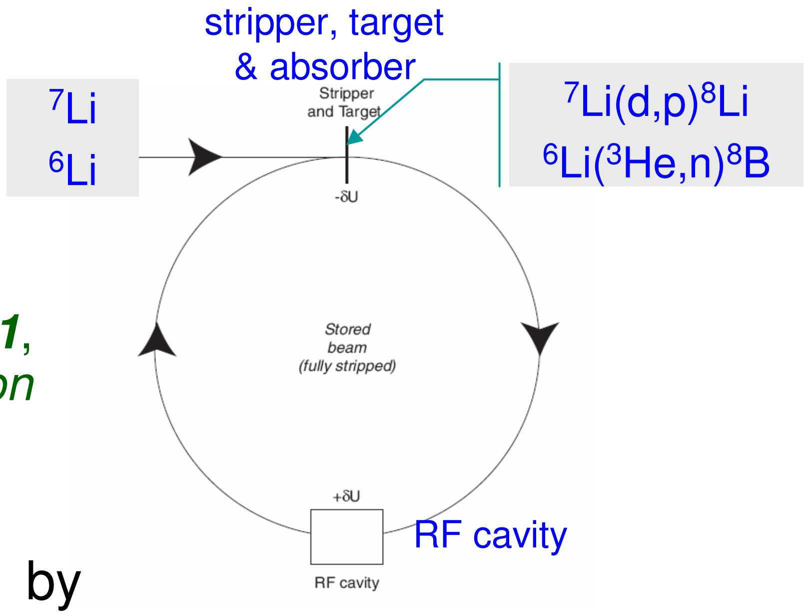


EURO-ν FP7

Production Ring

C. Rubbia, A. Ferrari, Y. Kadi, V. Vlachoudis, *Beam cooling with ionization losses,* ***NIM A 568 (2006) 475-487***

→ *see also* ***Y.Mori, NIM A 562 (2006) 591****, proton FFAG with internal Be target for neutron production* (but no need of (dp/p) cooling)



^{7}Li

^{6}Li

^{7}Li(d,p)^{8}Li

^{6}Li(^{3}He,n)^{8}B

- Enhance production ^{8}Li/^{8}B (~10^{14}/s) by multi passages trough a thin target
- Compact ring & internal target
- Inverse kinematics: Li beam @ ~25MeV and D or ^{3}He supersonic gas-jet target
- Multi Coulomb scattering + energy straggling @ target
- Ionization cooling

Ionization cooling

- Energy losses (dE/ds) in the target material (Bethe-Bloch)

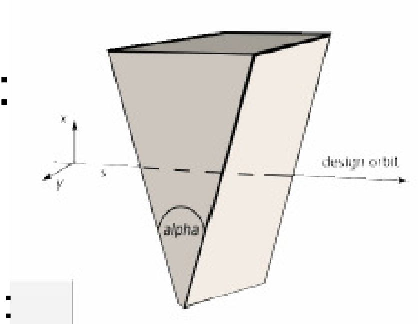
$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

- Only longitudinal component recovered in RF cavities

  → Transverse emittance shrinks

- Cooling in 6D
  - (dE/ds) ~ β^{-2} smaller at higher energies → cooling not effective in longitudinal
  - need coupling between transverse and longitudinal:

    → Dispersion & wedge-shaped target



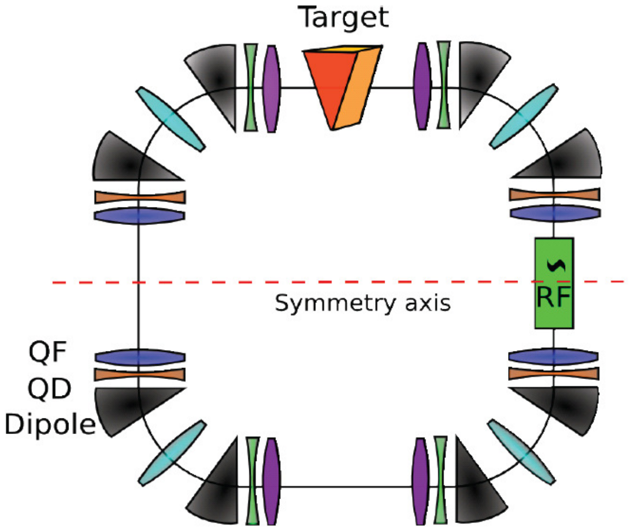
Faster ions will travel on an outer orbit and see a larger target thickness → they will get more (dE/ds)

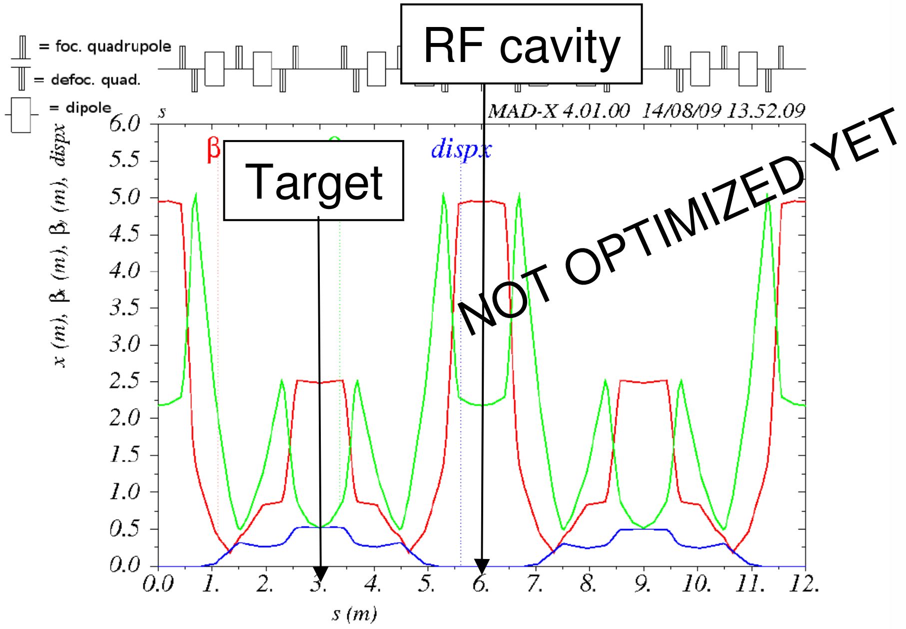
Target:
width @ closed orbit = 5 cm
t = 0.289 mg/cm^2
If angle = 20° → D_x> 24 cm

The proposed lattice

- 25 MeV ^{7}Li (βρ ~0.6)
- C = 12m
- 5 quadrupole families
- Normal-conducting magnets
- 2-fold mirror symmetry
  - RF cavity → in region D_x=0 m
  - Target → D_x~50cm

M. Schaumann, *CERN-THESIS-2009-128*





RF cavity

Target

NOT OPTIMIZED YET

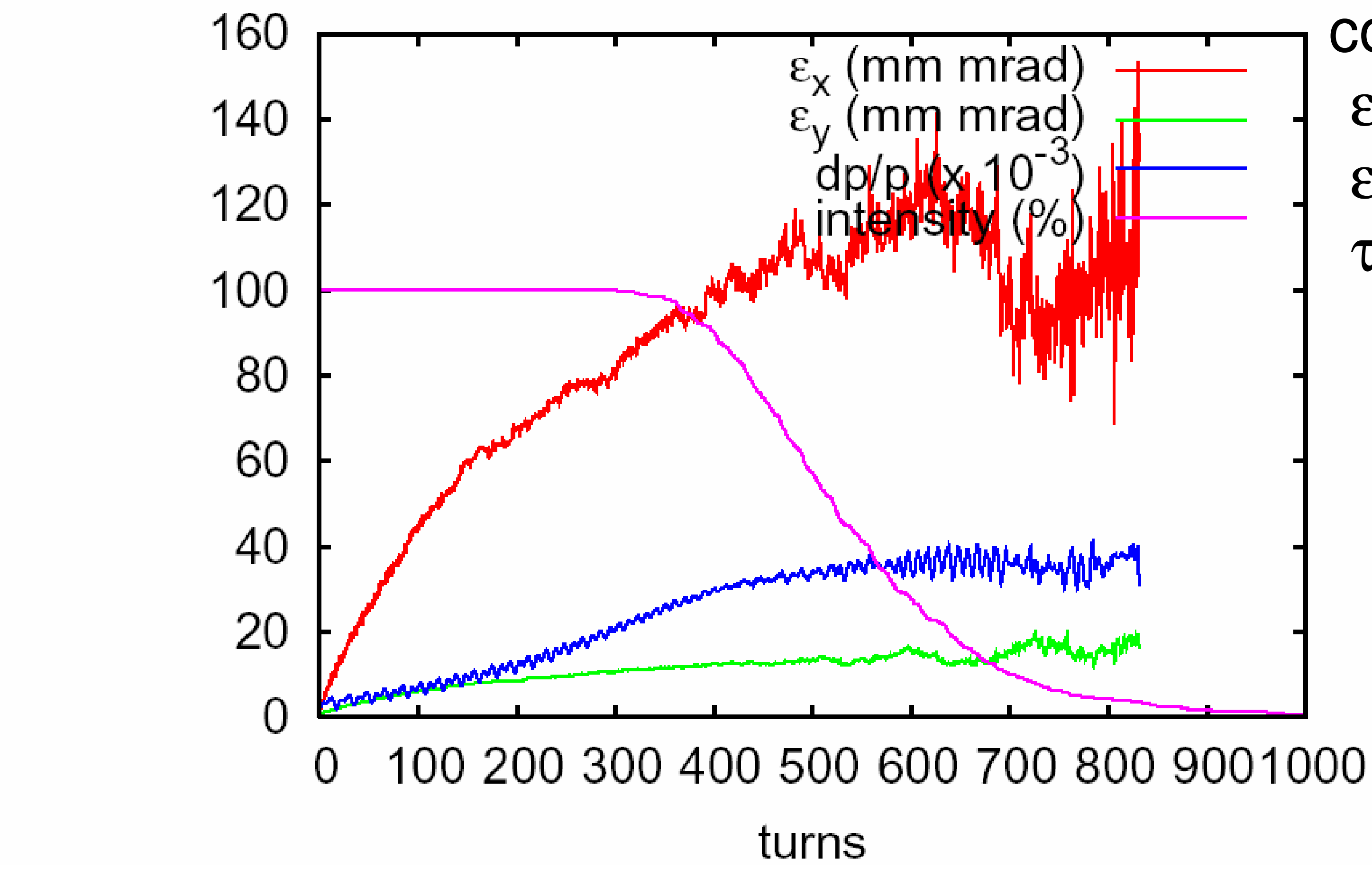
Particle		^{7}Li
Energy	E_c	25 MeV
Relativistic gamma	γ_r	1.00383
Beam rigidity	$B\rho$	0.636 T m
Transition γ	γ_t	3.58
Tune	$Q_{x,y}$	2.58, 1.63
Natural chromaticity	$Q'_{x,y}$	−3.67, −3.58
β @ target	$\beta^*_{x,y}$	2.62 m, 0.35 m
Dispersion @ target	$D^*_{x,y}$	0.523 m, 0 m
Target thickness	t_0	0.27 mg/cm^2
	n_t	10^{19} atoms/cm^2
Energy losses @ target	E_{BB}	∼ 0.30 MeV

Tracking simulations

- SixTrack (collimation version)
  - Developed at CERN for dynamic aperture tracking
  - Fully 6D, symplectic, reads lattice form MADX output (multipoles ok!)
  - Extended for LHC collimation & beam losses
  - Tracking large ensemble of halo particle
  - Interaction w. collimators

- Adapted to the Production Ring needs
  - Target implemented as a special collimator element:
    - Random transverse kick $\Delta x'$, $\Delta y'$ due to Multiple Coulomb scattering
      - (Gaussian distribution, $<\sigma_c^2>$)
    - Random energy losses ΔE :
      - mean value → Bethe-Bloch
      - energy straggling → gaussian distribution assumed
  - Rms emittances & Intensity evolution diagnostics
  - Sixtrack is for protons → need a proton equivalent ring (same $B\rho$, same $\Delta p/p$ recovered in RF cavity)

Tracking simulations: zero wedge angle



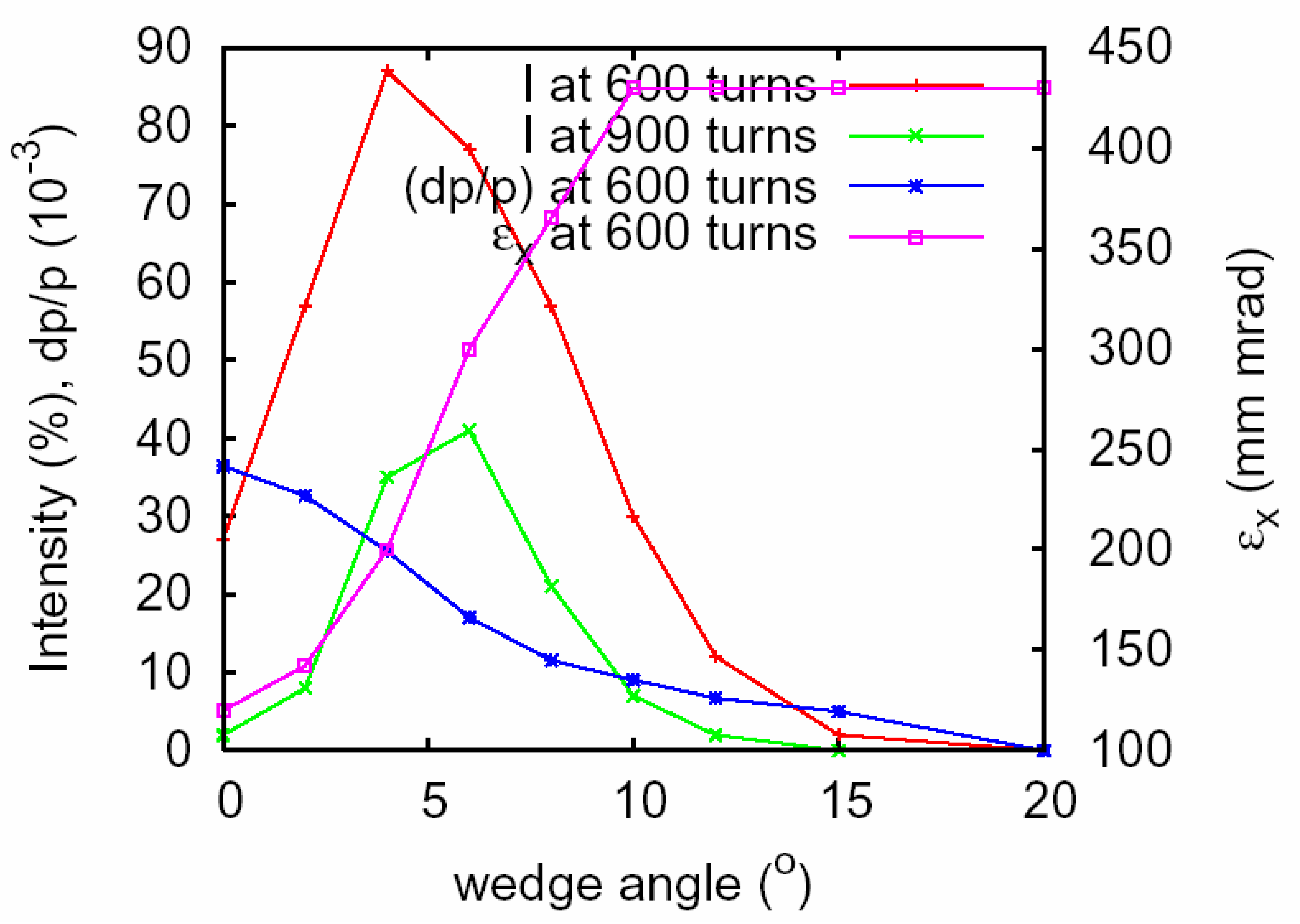
From analytical considerations:

ε_x~90 m

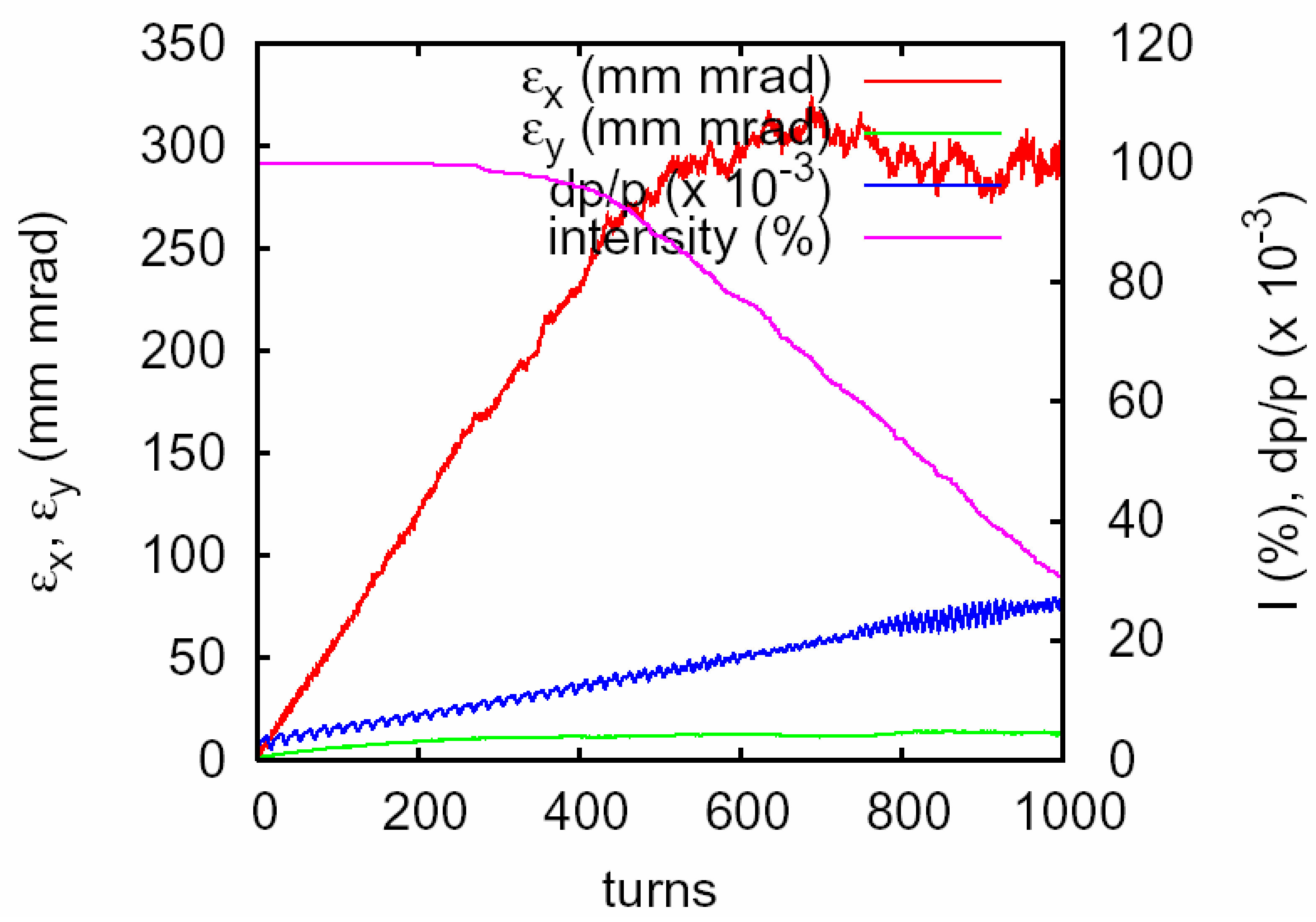
ε_y~11 m

τ ~ 170 turns

Tracking simulations: choice of the angle



Tracking simulations: wedge-angle =6°



Technological challenges

→ *Please refer also to my presentation at WP4 meeting in Paris*

- Supersonic gas jet target
  - Wedge shape (larger thickness for larger Δp/p)
  - Parameters

from C.Rubbia's:

Thickness	(mg/ cm^2) (atoms/cm^2)	0.27 **5 10^{19}**
Diameter	(cm)	5
Density	(mg/cm^3)	~0.06
Pressure	(Torr)	250
Mach n.	-	4
Nozzle throat	(mm)	3.26
P_plenum	(atm)	~3.5
Length	(cm)	~30

existing cluster-jet targets reach up to 10^{15} atoms/cm^2
→ Factor 10^4 missing

Technological challenges

- Possible solutions:
  - Increase injected beam intensity → already at limit of stable ^{7}Li ion source (~160 A required from the LINAC)
  - Run with poor vacuum (as long as the residual gas is thin compared to the target) → NO!, causes problems to the RF cavity (capacitive-loaded cavity)
  - Lower target density = less ion productions, but also = better lifetime & higher intensity circulating → more detailed studies are needed, another regime since Multiple Coulomb Scattering not valid any longer… → but gaining a factor 10^4, hmm…
- Other possibility: use D or ^{3}He beam & Lithium target (solid, waterfall, droplets,…?)
  - set-up lattice for cooling
  - study feasibility (power dissipation on target, collection,…)

Conclusions

- Tracking tools for i-cooling studies are now fully in place and benchmarked with analytical considerations
- Existing gas-jet targets cannot reach the densities proposed in [C.Rubbia, *et. al*] in a vacuum environment

Next Steps:

- Conclude AND document work on ring with gas-jet target
  - TO DO: implications of lower density target
  - TO DO: lattice optimization for i-cooling (i.e. reduce β^*)
- Study alternative solution: D(or ^{3}He) beam + Li target: (technological feasibility and i-cooling)
- Beam-target interaction:
  - Validity Bethe-Bloch & MultipleCoulombScattering for low densities
  - Production cross-section (& collection efficiency)

Back-up slides

Cooling rates and equilibrium emittance (1)

$$\frac{d\varepsilon_N}{ds} = -\frac{1}{p}\frac{dp}{ds}\varepsilon + \frac{\beta\gamma\ \beta_\perp}{2}\frac{d\left\langle\theta_c^2\right\rangle}{ds}$$

$$\boxed{\tau \sim \left(\int \frac{1}{p}\frac{dp}{ds}ds\right)^{-1} \approx 169 turns}$$

Damping time

$$\boxed{\varepsilon_\perp = \frac{1}{\beta\gamma}\frac{\beta\gamma\ \beta_\perp\left\langle\theta_c^2\right\rangle}{\int \frac{1}{p}\frac{dp}{ds}ds}}$$

Equilibrium emittances

$$\begin{cases} \varepsilon_x \sim 90 \quad \text{m} \\ \varepsilon_y \sim 11 \quad \text{m} \end{cases}$$

Cooling rates and equilibrium emittance (2)

$$\frac{d\sigma_E^2}{ds} = -2\underbrace{\frac{\partial}{\partial E}\left(\frac{dE}{ds}\right)\sigma_E^2}_{<0\ \to\ \text{blow-up}} + \frac{d\Delta E_{str}^2}{ds}$$

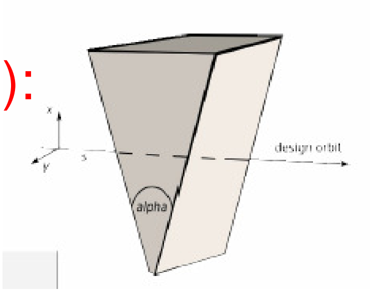
straggling

$$\boxed{\frac{d\varepsilon_z}{ds} = -\frac{J_z}{p}\frac{dp}{ds}\varepsilon + \dots}$$

$$\boxed{J_z = \frac{\partial}{\partial E}\left(\frac{dE}{ds}\right)\left(\frac{1}{p}\frac{dp}{s}\right)^{-1}}$$

<0 !!!!

If now we introduce Dispersion (and a triangular target shape):



$$\frac{\partial}{\partial E}\left(\frac{dE}{ds}\right) = \frac{\partial}{\partial E}\left(\frac{dE}{ds}\right)\Bigg|_{\Delta x=0} + \underbrace{\left(\frac{dE}{ds}\right)\frac{1}{\rho_0}\frac{d\rho}{dx}\frac{D}{\beta c p}}_{\text{at a different orbit } \Delta x = D\ \Delta p/p}$$

Cooling rates and equilibrium emittance (3)

If now we introduce Dispersion (and a triangular target shape):..

$$\boxed{J_z \rightarrow J_z + \frac{D}{\rho_0}\frac{d\rho}{dx}}$$

$$\boxed{J_x \rightarrow J_x - \frac{D}{\rho_0}\frac{d\rho}{dx}} \quad \boxed{J_y \rightarrow J_y}$$

can also introduce coupling x-y

Cooling can be transferred from transverse to longitudinal thanks to Dispersion + triangular target

Since sum of the three partition number is always the same, is computed for $D_x=0$:

$$\sum J_i = 1 + 1 + \frac{\partial}{\partial E}\left(\frac{dE}{ds}\right)\Big|_{\Delta x=0} \begin{cases} 0.4 & \text{for } {}^{6}\text{Li} \\ 0.01 & \text{for } {}^{7}\text{Li} \end{cases}$$

Due to Bethe-Bloch shape, NO possibility to effectively cool → but only to keep a constant emittance or not to heat it “too much”