NUFACT10, XII International Workshop
20 - 25 October 2010
Tata Institute of Fundamental Research, Mumbai

Beta Beam: How do we reach wanted intensities?

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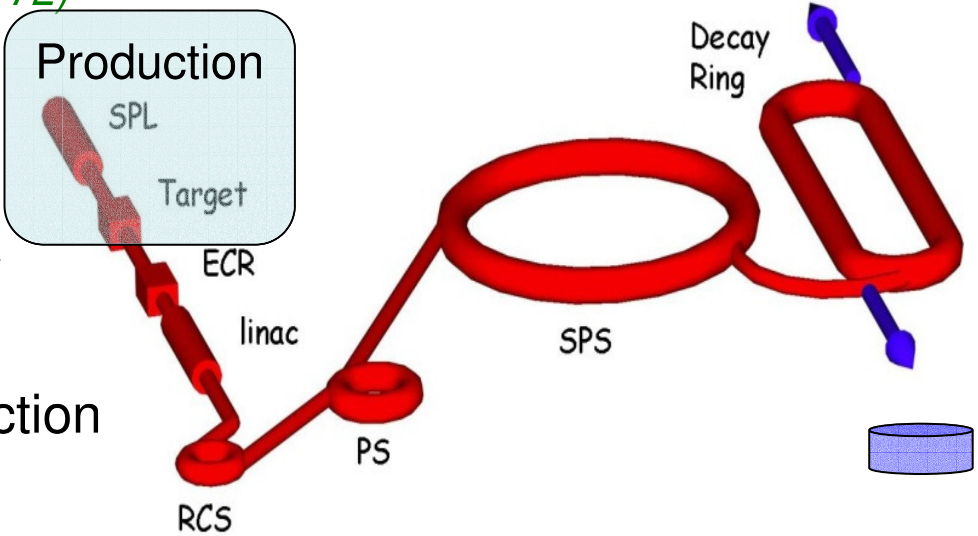
NTU-Athens & CERN

- Beta Beams, the idea, the ions, the required intensity
- How to get there
  - Production + Collection
  - Acceleration & transmission efficiency
  - Storage
- Challenges and strategies

Beta-Beams: the idea

- Aim: production of electron (anti-)neutrino beams from β-decay of radioactive ions circulating in a storage ring
  (P. Zucchelli, Phys. Let. B, 532 (2002)166-172)



- **Produce** suitable radio-isotopes
- **Accelerate** the ions
- **Store** them in a racetrack Decay Ring (DR)
- **Let them β-decay** (a straight section of the DR points to detector)
- **Pure ν_e/anti-ν_e** are emitted (need a pair of β^+/β^- emitters)
  - with a known energy spectrum ($E_\nu < 2\gamma Q$)
  - in forward direction, (cone $\theta < 1/\gamma$)

Q = Reaction Energy ~ few MeV

1st design study makes max. use of existing CERN infrastructures.

Beta-Beams: the ions

- **Need a pair of neutrino and antineutrino emitters**
  - **Lifetime at rest**: $\tau_{1/2}$~1s
  - **Low Z** (minimize accelerated mass/charge & reduce space-charge)
  - **Production rates**
- Stored in a race-track Decay Ring at γ=100
- Q = Reaction Energy

"Low-Q" isotopes

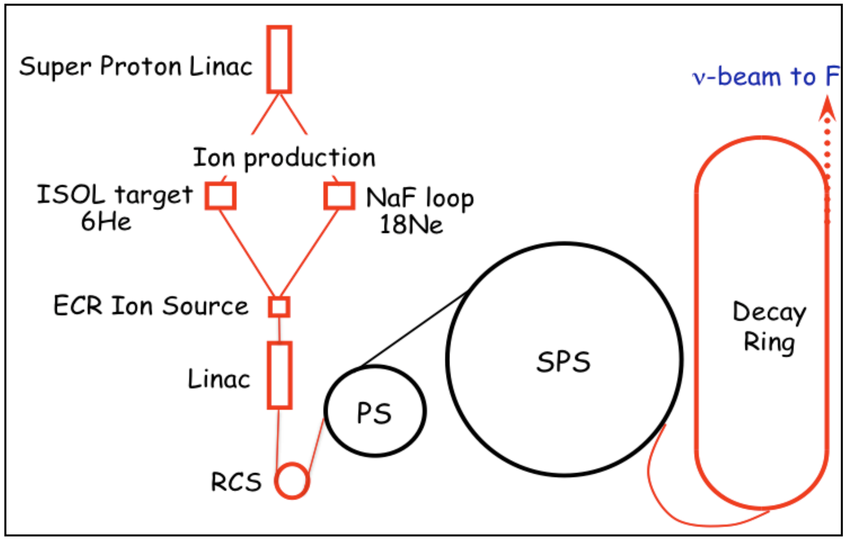
Isotope	^{6}*He*	^{18}*Ne*
A/Z	*3*	*1.8*
emitter	β^-	β^+
$\tau_{1/2}$ *(s)*	*0.81*	*1.67*
Q (MeV)	*3.51*	*3.0*

"High-Q" isotopes

Isotope	^{8}*Li*	^{8}*B*
A/Z	*2.7*	*1.6*
Emitter	β^-	β^+
$\tau_{1/2}$ *(s)*	*0.83*	*0.77*
Q (MeV)	*12.96*	*13.92*

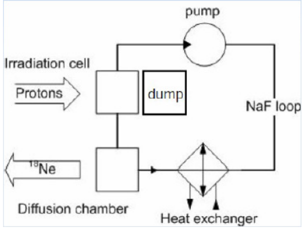
Beta-Beams: the 2 scenarios

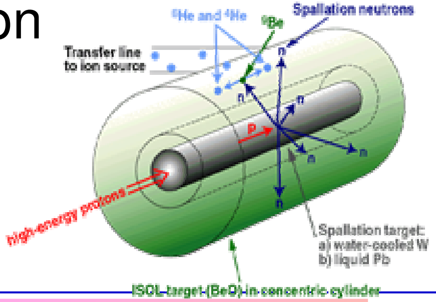
- ^{6}He,^{18}Ne



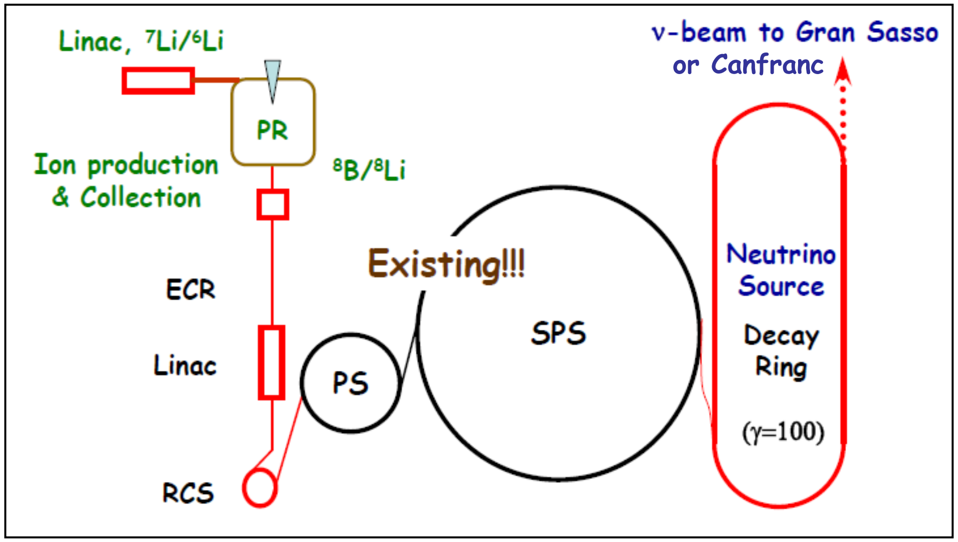
- Detector @ Frejus (L=130 Km)

- ISOL production





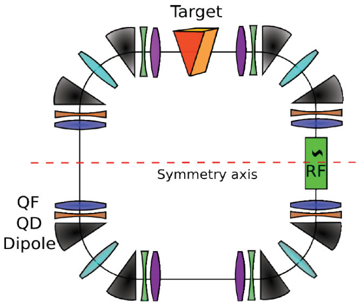
- ^{8}Li, ^{8}B (high Q)



- Longer baseline (L=~700 Km)

- Production Ring

C.Rubbia et al, NIM A 568 (2006) 475–487



Beta-Beams: the wanted intensities (1)

- Annual (10^7s) neutrino rate x 10 years run:
  - 2.9 10^{18} anti-neutrinos from ^{6}He
  - 1.1 10^{18} neutrinos from ^{18}Ne
- Corresponding to the production (@ source) of:
  - 3(.3) 10^{13}/s ^{6}He
  - 2(.1) 10^{13}/s ^{18}Ne

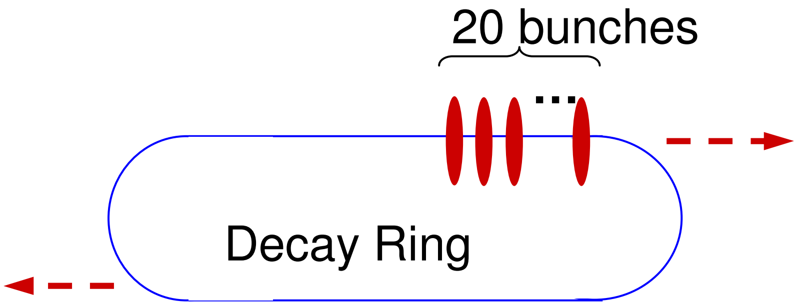
- High Q isotopes (^{8}Li, ^{8}B)
  - $Q \sim 3.5 \times Q_{(He, Ne)}$, $\gamma = 100$ (from SPS)
  - Longer baseline: $L \sim \langle E_\nu \rangle / \Delta m^2 \sim \gamma Q$ => Flux ~ $L^{-2} \sim Q^{-2}$
  - Cross section ~ $\langle E_\nu \rangle \sim \gamma Q$

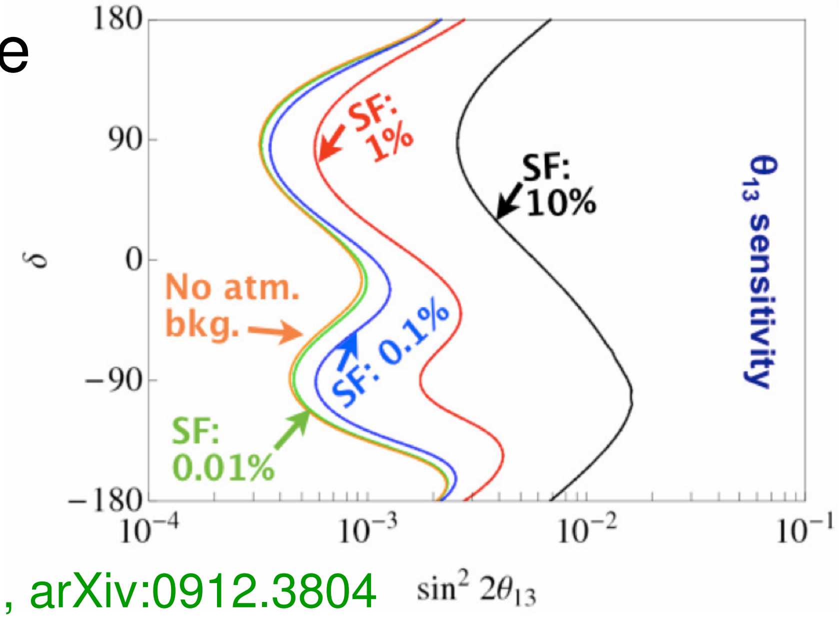
Need a factor ~5 more intensity than for ^{6}He,^{18}Ne

Beta-Beams: the wanted intensities (2)

- To suppress ν atmospheric background
  - Ions are bunched and occupy only a fraction of the Decay Ring
  - The detector is triggered to the bunch passage
- Suppression Factor (=Duty Factor) between 0.1% and 1% is needed

$$SF = DF = \frac{Nl}{L}$$





E.Martinez, arXiv:0912.3804

How to reach wanted intensities?

- Store as much as possible
- Accelerate as fast as possible
- Transmission efficiency
- Production rates

Challenges and R&D

High intensity beams → Collective effects

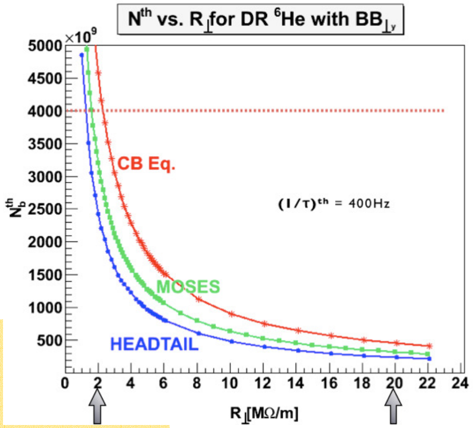
Radio-isotopes: production, collection, ionization

Beam loading in RF cavities

Radioprotection, pressure rise, collimation

Decay ring

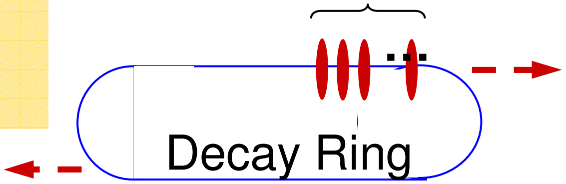
- Store as much as possible
- HIgh intensity beam
  - Nb=10^{13} ions/bunch (10ns bunch length)



- Collective effects
  - → see C.Hansen's talk (CERN)
- Power deposition (losses and collimation)
  - → E.Wildner, E.Bouquerel (CERN)

- Atmospheric bkg suppression
  - 20 bunches in 1% of the ring

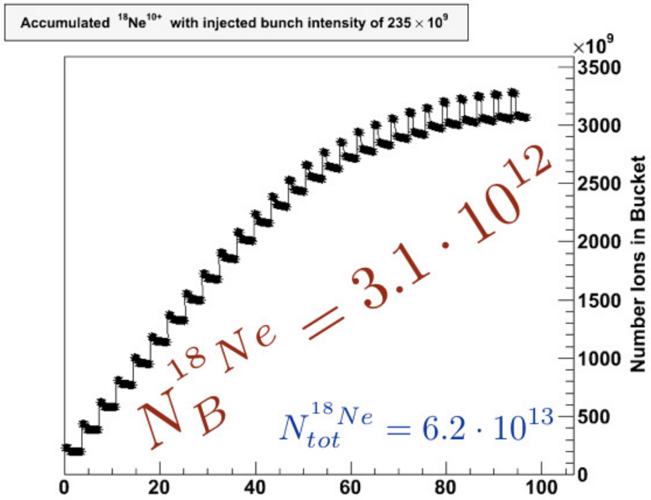
- RF cavity transient beam loading
  - → G.Burt, (Cockcroft Institute, UK) started



Decay Ring

- RF Stacking
  - Needs multiturn injection
  - After 15-20 beam merges, about 50% particles outside RF acceptance
  - Momentum collimation

- Power deposition

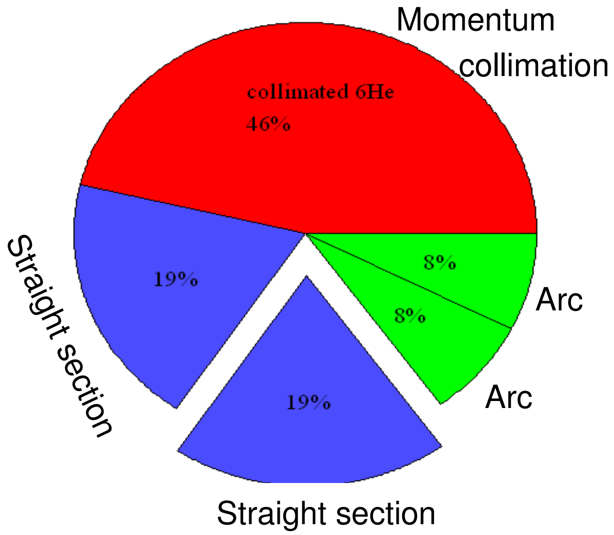


D. Heinrich, A. Chance, C. Hansen

- Only β-decays in 1 straigth section useful

- DR optimization (reduce arc length)
  → A.Chance, J. Payet (CEA), E.Wildner (CERN)

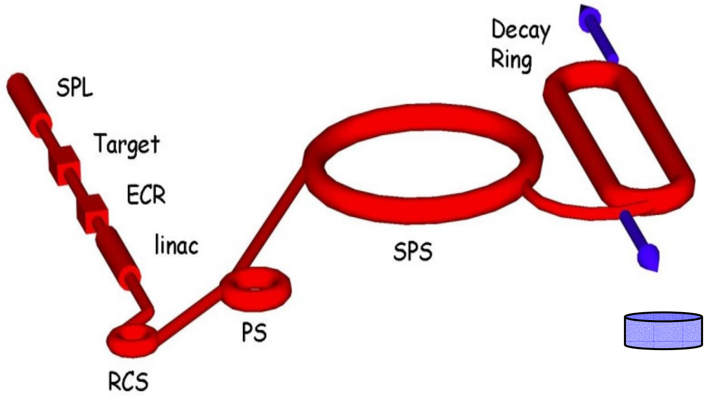
~50% lost due to momentum collimation
Only ~20% useful decays

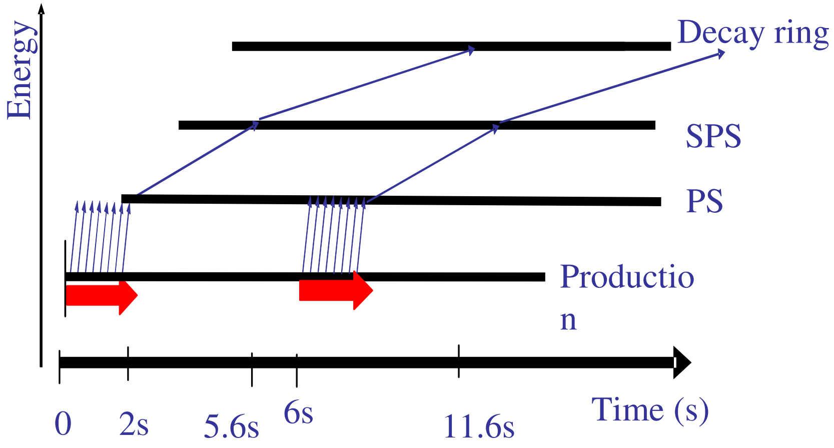


Accelerator chain

- Transmission efficiency
  - – Minimize losses
- Fast acceleration & avoid “dead time”
  - – PS ramp-rate: 3.6s
  - – SPS ramp-rate: 3.6s for ^{6}He and 6s for ^{18}Ne
  - – Decay losses: only 50% ^{6}He and 80% ^{18}Ne reach DR

- Greenfield scenario? → M. Martini, E.Wildner, CERN





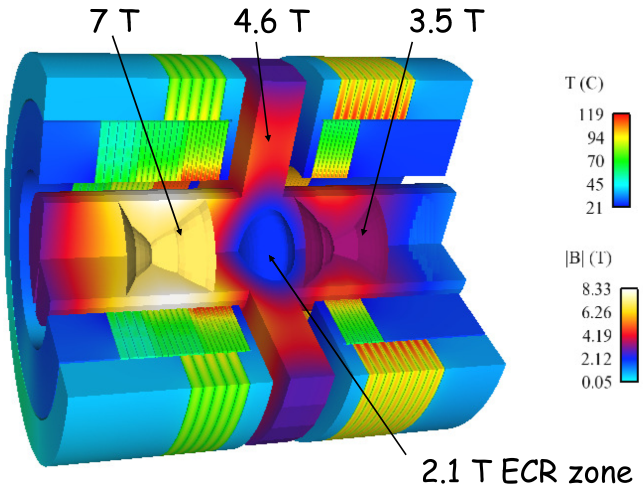
Acceleration chain: Source

- ECR Source
  - Pulsed!!!
  - Re-Ionization (+1) isotopes
  - Provides 50μs pulses
  - Operating at 10Hz

Efficiency:

He^{1+} ~ 30%
Ne^{1+} ~ 20%, Ne^{+6} ~ 20%

Li^{1+}, B^{1+} ~ 5%,



- R&D to get to higher efficiency:
  - High (60GHz) ECR frequency, conventional is 20GHz
  - Magnetic tests ongoing in Grenoble test facility LNPC
    - → T. Lamy's (CNRS) team
  - Short pulse generation studies
    - → V.Zorin, (INP)

Acceleration chain: Linac

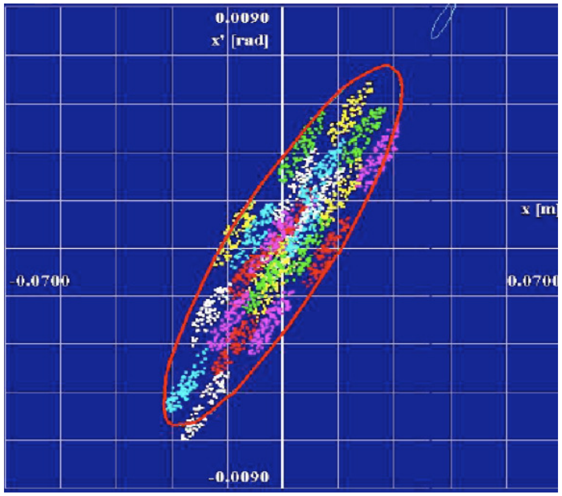
- Linac: first stage acceleration
  - Source produces 50μs pulse every 0.1s (10Hz)
  - Linac accelerates to 100MeV/nucleon
  - RFQ efficiency 90% (if carefully designed)
- Stripping foil
  - Source produces ions^{+1} (higher efficiency)
  - Stripping foil to have He^{2+}, Ne^{+10} ions
  - Ok!

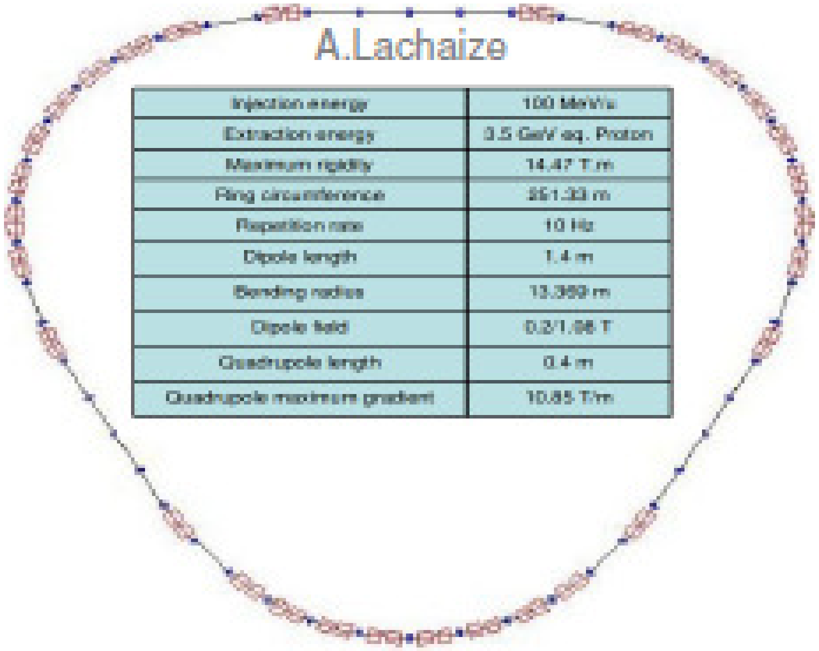
- Careful RFQ design
- No particular challenges

- Efficiency: ~ 90%

Acceleration chain: RCS

- Rapid Cycling Synchrotron (RCS)
  - Very fast acceleration in 0.1s
  - Multiturn injection to accomodate 50μs pulse




A.Lachaize

Injection energy	100 MeV/u
Extraction energy	3.5 GeV eq. Proton
Maximum rigidity	14.47 T.m
Ring circumference	251.33 m
Repetition rate	10 Hz
Dipole length	1.4 m
Bending radius	13.369 m
Dipole field	0.2/1.08 T
Quadrupole length	0.4 m
Quadrupole maximum gradient	10.85 T/m

Losses:

20% multiturn injection
2% decay
10% RF capture

Acceleration chain: PS & SPS

- PS & SPS
  - – Accelerate beam up to γ=100
  - – Existing @CERN
    - They are "for free"
    - Not optimized for BetaBeams
    - Quite "long" acceleration ramp
      - – Decays & "dead time"

Losses

50% decays for ^{6}He
20% decays for ^{18}Ne

- Need additional 40MHz cavities in SPS
- Radioprotection OK!
- High intensity collective effects

Production: requirements

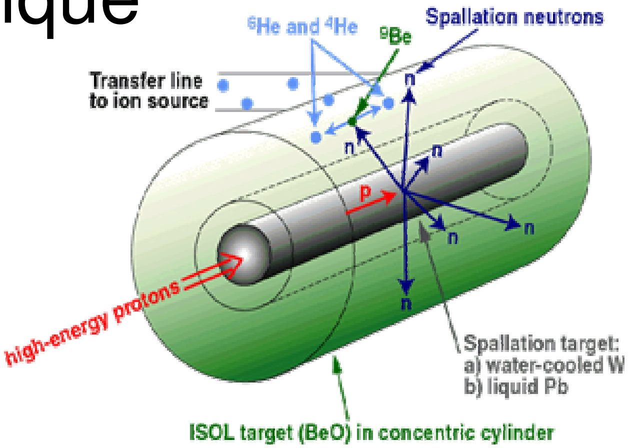
- Summing-up all losses in accelerator chain
  - Source + Linac RFQ: ~70%
  - RCS injection+capture: 30%
  - Decay losses: 20%(^{18}Ne) 50%(^{6}He)
  - Momentum collimation: up to 50%

- Only 8.4%(^{18}Ne)-5.2%(^{6}He) of produced ions is stored in the DR

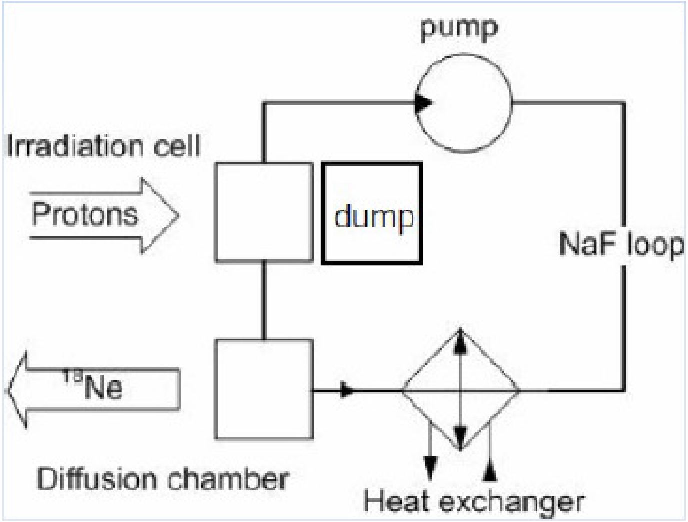
⇨ We need to produce (and collect!!!)
2-3 10^{13} (x5) ions/s

Production (low Q isotopes)

- ^{6}He →“standard” ISOL(DE) technique
  - Linac4 or SPL or GANL, SoreQ, ...
    - 3 10^{13} ions/s
    - OK! (even more than needs)

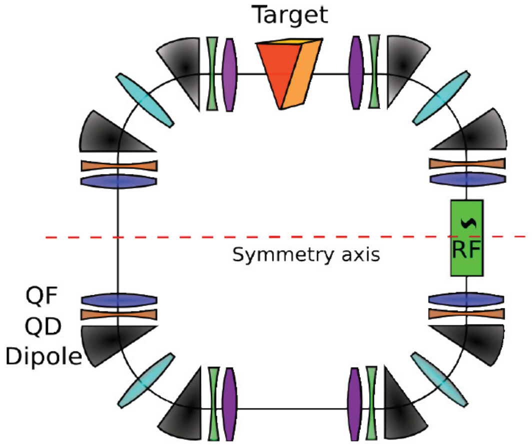


- ^{18}Ne → molten salt loop +ISOL
  - Linac4
    → Studies by P.Valko and T.Stora (CERN)
    - 2 10^{13} ions/s
    - Promising but NEEDS EXPERIMENTS!!!
    - (with ISOL, factor 20 missing)
- We can avoid MW targets



Production (high Q isotopes)

- ^{8}Li, ^{8}B isotopes
  - Originally considered to overcome lack of ^{18}Ne
  - (they also have longer baseline)
  - Studies started in 2009, within EUROnu(*)
- Production ring
  - Multi-passage through an internal target
  - Ionization cooling
    - → *see **C.Rubbia et al, NIM A 568 (2006) 475–487***
    - → *see **D. Neuffer, NIM A 585 (2008) 109***



→ E.B (NTU-Athens & CERN) M.Schaumann (RTWH Aachen)

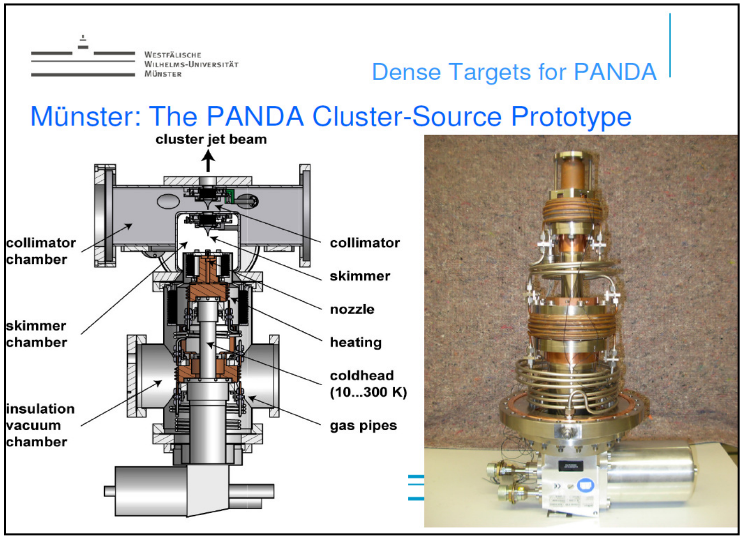
(*) FP7 "Design Studies" (Research Infrastructures) EUROnu (Grant agreement no.: 212372)

Production (high Q isotopes)

- Production ring, challenges
  - High density gas-jet target in vacuum environment
    - Factor 10^4 missing

      (from present research)

      → *E.B. (NTU-Athens, CERN)*

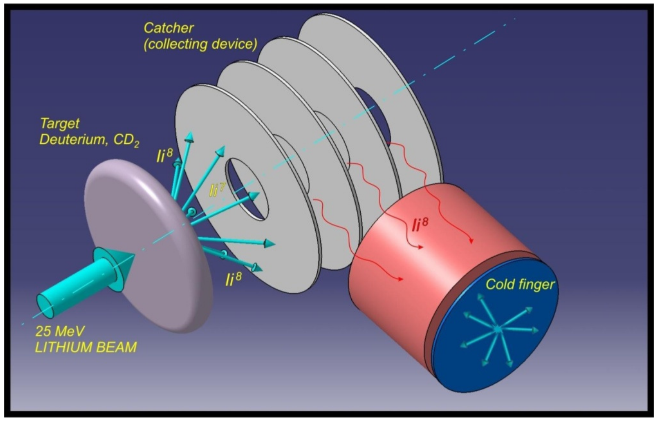


Westfälische Wilhelms-Universität Münster

Dense Targets for PANDA

Münster: The PANDA Cluster-Source Prototype

  - Collection device investigation

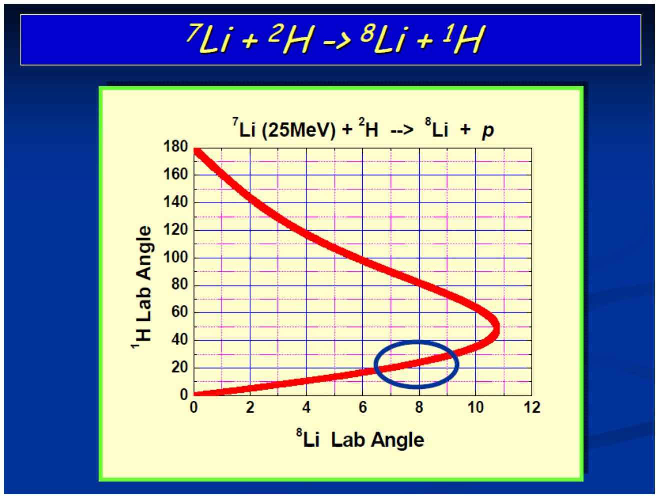


- Measurement set-up ready for ^{8}Li
- ^{8}B will follow...chemistry?

→ *S. Mitrofanov, T. Delbar, M. Loiselet, CRC, Louvain La Neuve*

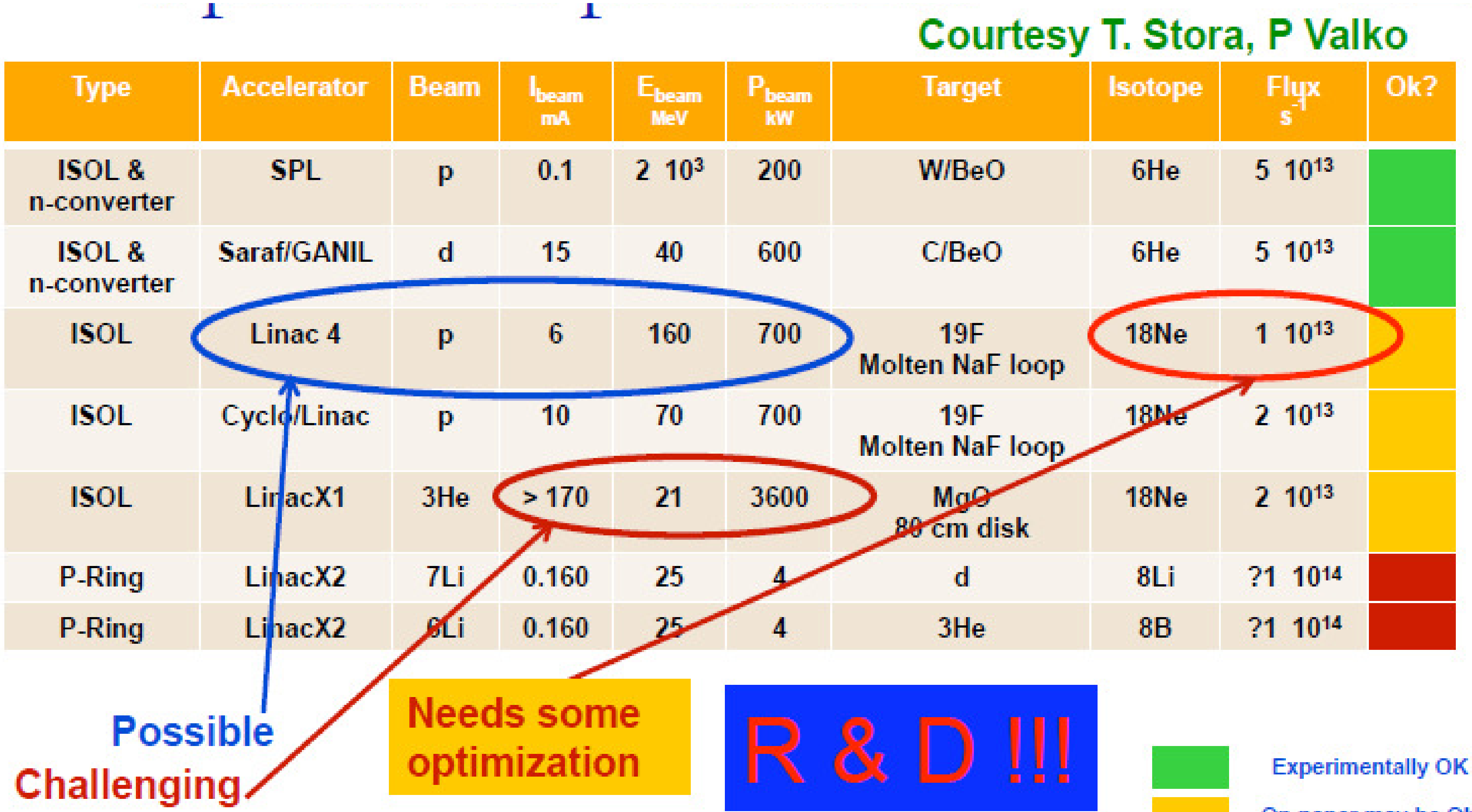
Production (high Q isotopes)

- Production ring, alternative solutions
  - Direct kinematics + solid/liquid target
    - → *T. Weber (RTWH Aachen) and E.B., started*
  - May use existing CERN ring (LEIR, AD,…) → *E.B., next*
  - …or an FFAG → *see Y. Mori, NIM A 562 (2006) 591-595*
- Production ring, interaction beam-target



  - Interaction beam-matter modeling
    - → *V.Vlauchoudis, D.Sinuela, E.B. (CERN)*
  - Cross-section measurements and angular distribution direct/indirect kinematic at low energy
    - → M. Cinausero, G. De Angelis, G. Prete, (INFN-LNL), E. Vardaci (INFN-Napoli)

Production (summary)



Courtesy T. Stora, P Valko

Type	Accelerator	Beam	I_{beam} mA	E_{beam} MeV	P_{beam} kW	Target	Isotope	Flux s^{-1}	Ok?
ISOL & n-converter	SPL	p	0.1	$2\ 10^3$	200	W/BeO	6He	$5\ 10^{13}$	🟩
ISOL & n-converter	Saraf/GANIL	d	15	40	600	C/BeO	6He	$5\ 10^{13}$	🟩
ISOL	Linac 4	p	6	160	700	19F Molten NaF loop	18Ne	$1\ 10^{13}$	🟨
ISOL	Cyclo/Linac	p	10	70	700	19F Molten NaF loop	18Ne	$2\ 10^{13}$	🟨
ISOL	LinacX1	3He	> 170	21	3600	MgO 80 cm disk	18Ne	$2\ 10^{13}$	🟨
P-Ring	LinacX2	7Li	0.160	25	4	d	8Li	$?1\ 10^{14}$	🟥
P-Ring	LinacX2	6Li	0.160	25	4	3He	8B	$?1\ 10^{14}$	🟥

Possible

Challenging

Needs some optimization

R & D !!!

🟩 Experimentally OK

🟨 On paper may be OK

🟥 Not OK yet

Li can be produced by similar methods as 6He in good amounts

Conclusions (1)

- Present baseline: ^{6}He and ^{18}Ne (CERN Frejus)
- Top-down approach: according to losses in the chain, identify how many ions @ the source
- Production:
  - ^{6}He OK,
  - ^{18}Ne promising, BUT need experimental verification!
- R&D for higher-Q ions ^{8}Li and ^{8}B (L ~ 700 km)
  - Need ~5 times more intensity, but maybe advantages of longer baseline
  - Production still challenging (but in 2006 the idea, in 2009 started investigation)

Conclusions (2)

- BetaBeams is based on existing technology and (if possible) on CERN existing infrastructures
  - ISOLDE infrastructure ☺
  - Saving on costs ☺
  - PS &SPS not optimized for Beta Beams ☹
- Challenges due to high intensities are identified all along the chain:
  - Production, acceleration and storage
  - High intensity collective effects, Collimation in DR, small Duty Factor, Ion production, Radioprotection,..
- R&D is ongoing to find mitigation/alternatives

Acknowledgements

- E. Wildner, C. Hansen, G. Arduini, R.Garoby, E. Metral, A. Lachaize, M. Lindroos, T. Stora,...

- EUROnu WP4 contributing institutes and partecipants:
  - CERN, Switzerland
  - CEA, CNRS, LPSC, LNCMI, France
  - INFN, Italy
  - LLN, CRC, Belgium

- And associate partners:
  - INP, Russia
  - RTWH Aachen, GSI, Germany
  - Cockcroft Institute, UK