A BASELINE BETA-BEAM

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on behalf of the
EURISOL Beta-beam task

http://cern.ch/beta-beam/

Outline

- **Beta-beam**
  - **First study in 2002: ion choice, main parameters**
  - **Ion production**
  - **Asymmetric bunch merging for stacking in the decay ring**
  - **Decay ring optics design & injection**
- **The EURISOL DS**
- **Challenges for the Beta-beam R&D**
- **Conclusions**

Introduction to beta-beams

- **Beta-beam proposal by Piero Zucchelli**
  - ***A novel concept for a neutrino factory: the beta-beam*, Phys. Let. B, 532 (2002) 166-172.**

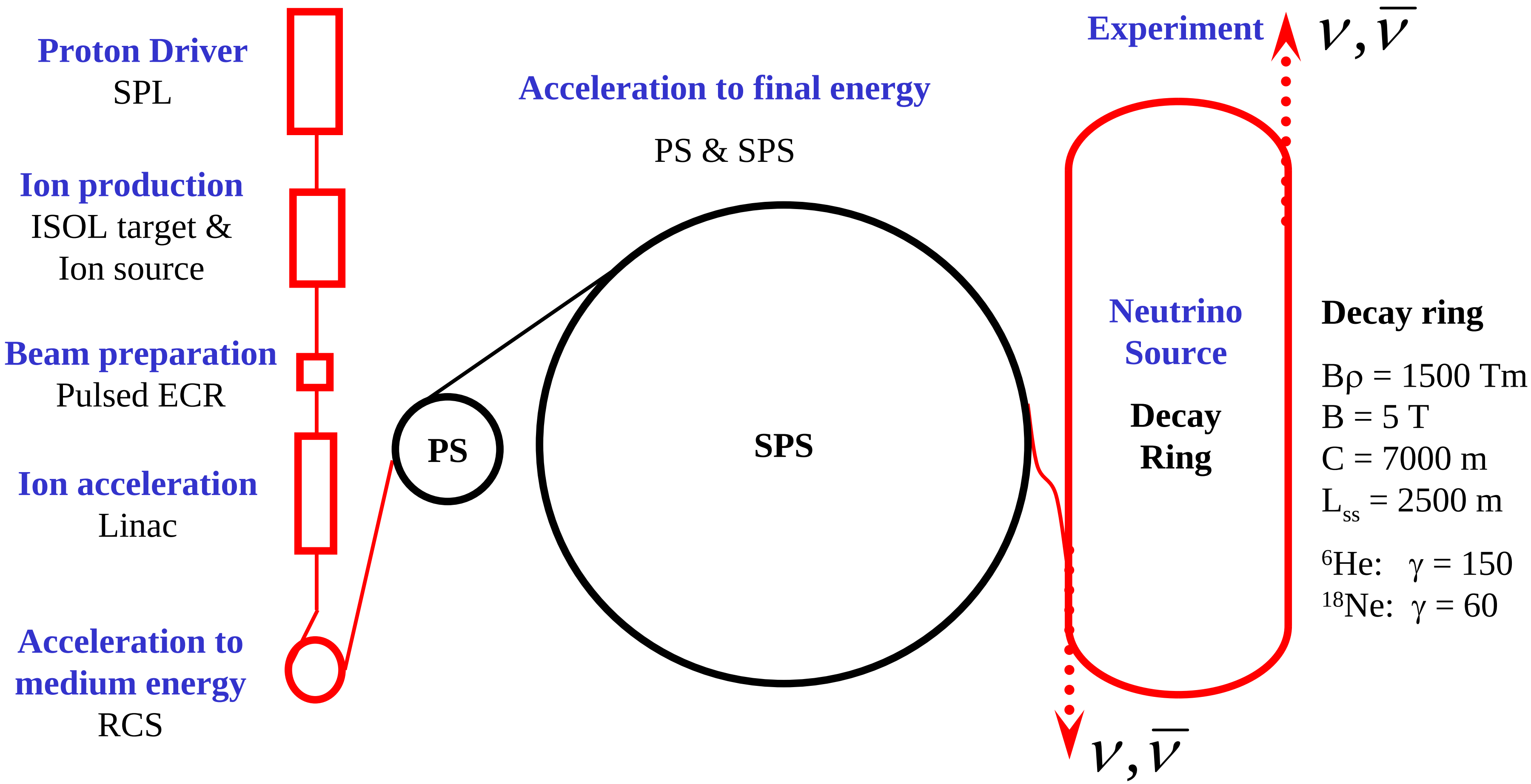
- **AIM: production of a pure beam of electron neutrinos (or antineutrinos) through the beta decay of radioactive ions circulating in a high-energy (γ~100) storage ring.**

- **First study in 2002**
  - **Make maximum use of the existing infrastructure.**

Beta-beam

NuFact 05

Ion production **Acceleration** **Neutrino source**



Main parameters

- **Factors influencing ion choice**
  - **Need to produce reasonable amounts of ions.**
  - **Noble gases preferred - simple diffusion out of target, gaseous at room temperature.**
  - **Not too short half-life to get reasonable intensities.**
  - **Not too long half-life as otherwise no decay at high energy.**
  - **Avoid potentially dangerous and long-lived decay products.**

- **Best compromise**
  - **Helium-6 to produce antineutrinos:** ${}^{6}_{2}He \rightarrow {}^{6}_{3}Li\ e^{-}\ \bar{\nu}$

    Average $E_{cms} = 1.937$ MeV
  - **Neon-18 to produce neutrinos:** ${}^{18}_{10}Ne \rightarrow {}^{18}_{9}F\ e^{+}\ \nu$

    Average $E_{cms} = 1.86$ MeV

FLUX

- The first study "Beta-beam" was aiming for:
  - A beta-beam facility that will run for a "normalized" year of 10^7 seconds
  - An annual rate of 2.9 10^{18} anti-neutrinos (^6He) and 1.1 10^{18} neutrinos (^{18}Ne) at γ=100

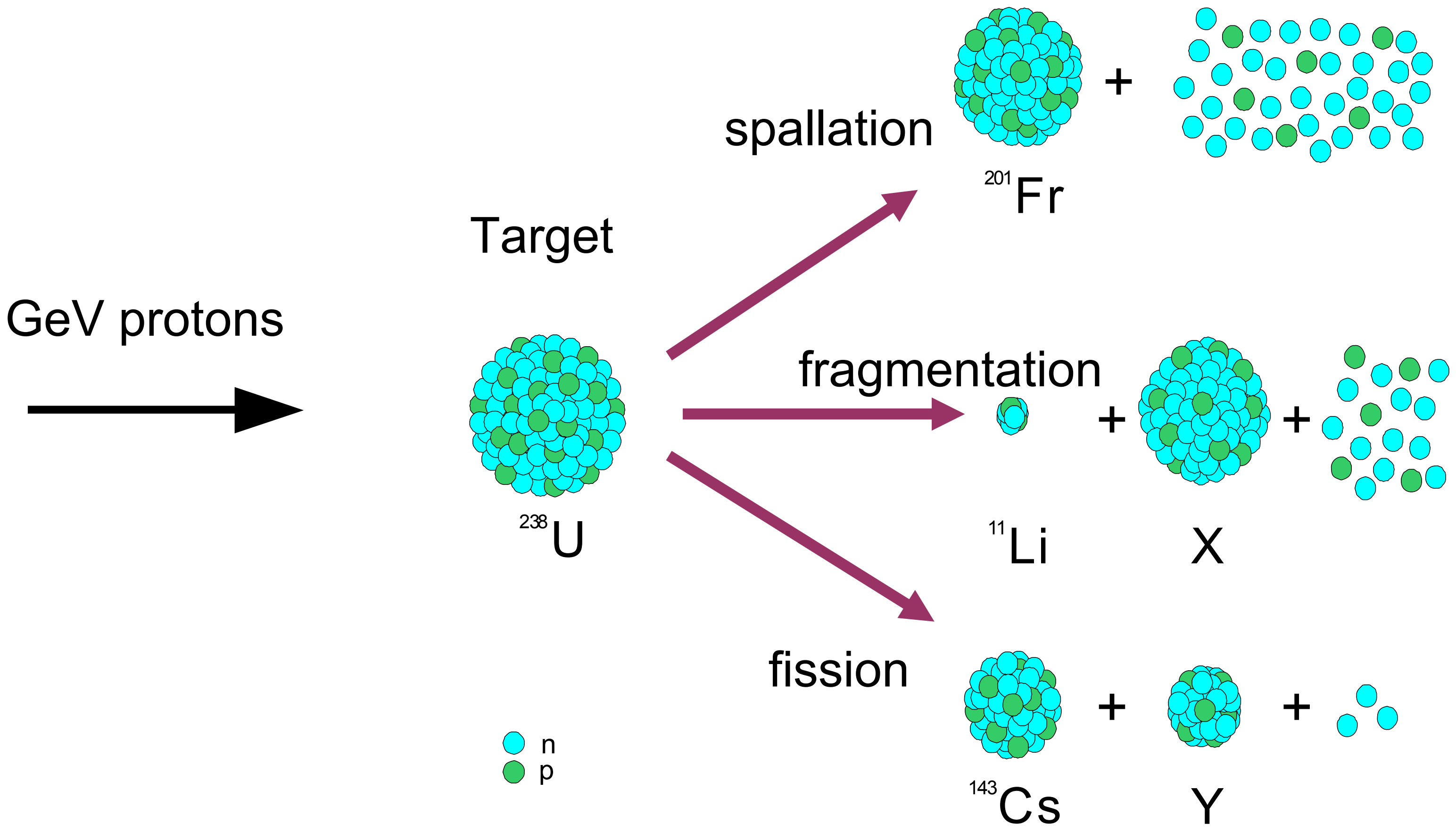
with an Ion production in the target to the ECR source:

  - ^6He= 2 10^{13} atoms per second
  - ^{18}Ne= 8 10^{11} atoms per second

- The often quoted beta-beam facility flux for ten years running is:
  - anti-neutrinos: 29 10^{18} decays along one straight section
  - Neutrinos: 11 10^{18} decays along one straight section

Ion production - ISOL method

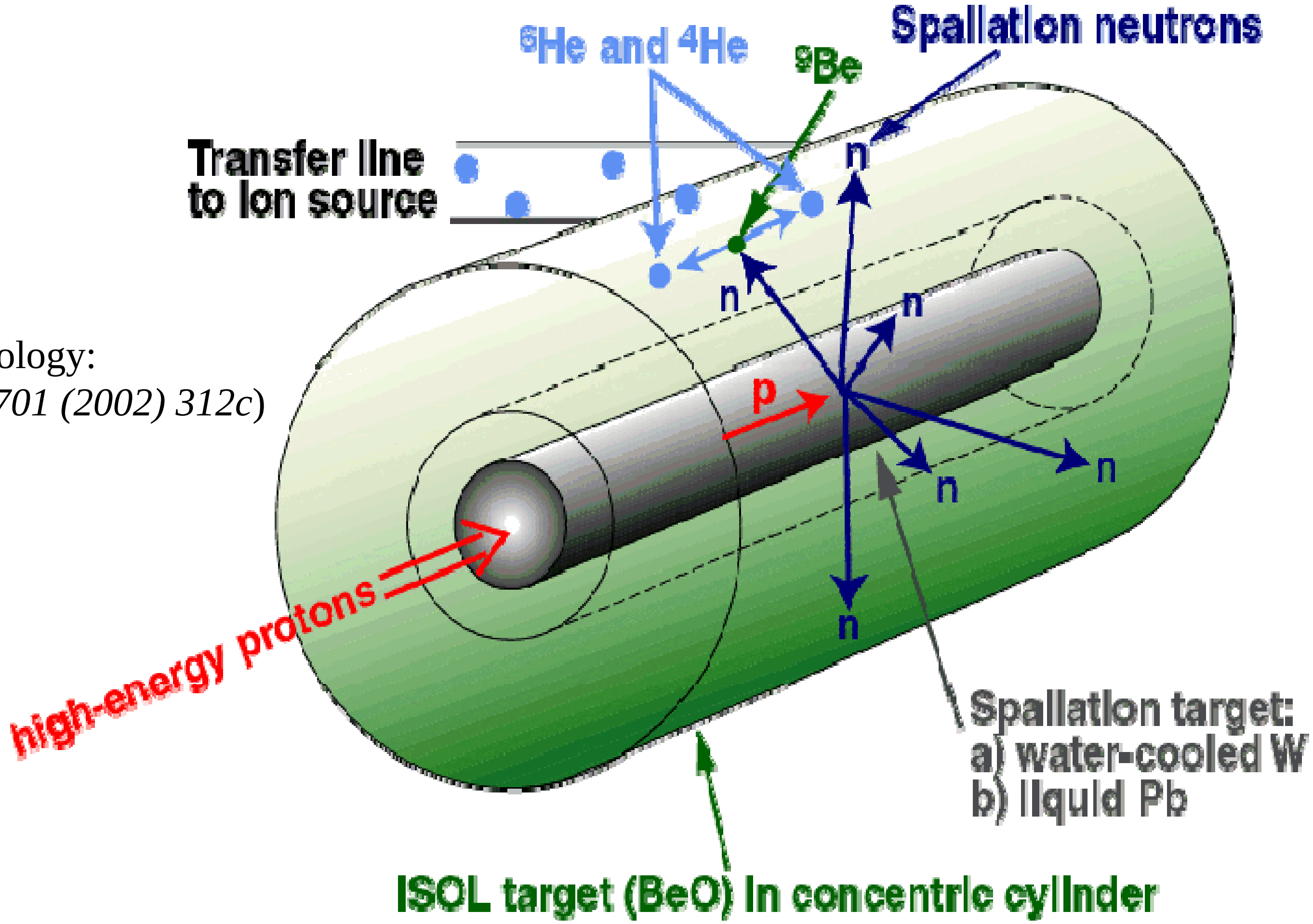
- **Isotope Separation OnLine method.**
- **Few GeV proton beam onto fixed target.**



^{6}He via spallation n

^{18}Ne directly

^{6}He production from ^{9}Be(n,α)



Converter technology:
(*J. Nolen, NPA 701 (2002) 312c*)

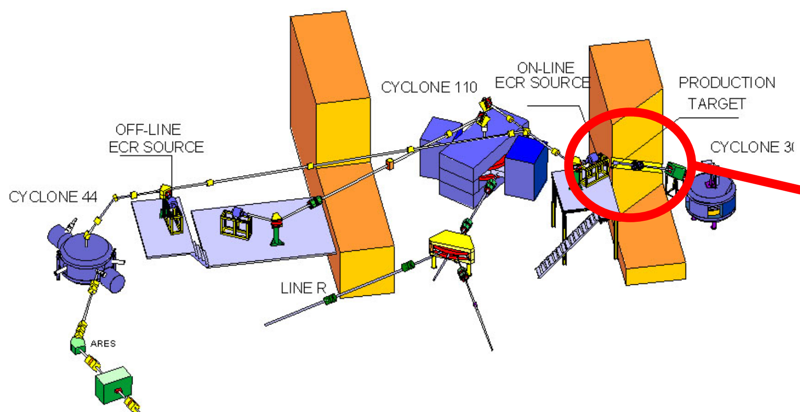
- **Converter technology preferred to direct irradiation (heat transfer and efficient cooling allows higher power compared to insulating BeO).**
- **^{6}He production rate is ~2x10^{13} ions/s (dc) for ~200 kW on target.**

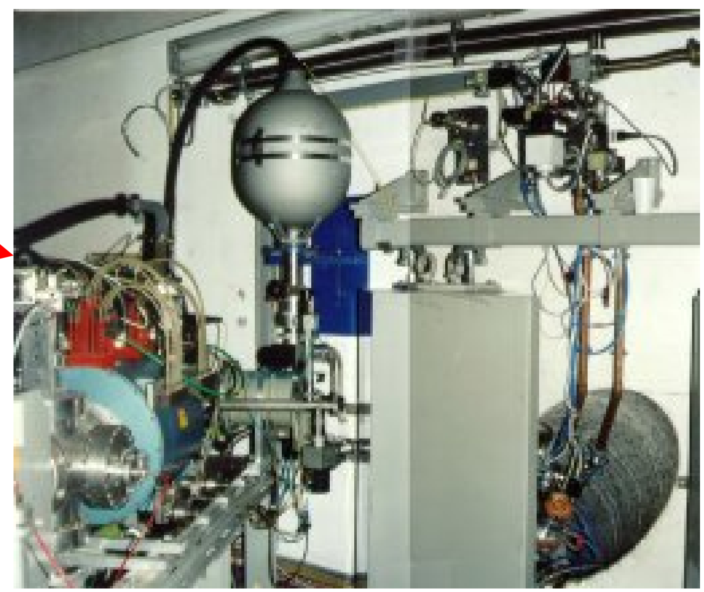
^{18}Ne production

- **Spallation of close-by target nuclides**
  - **$^{24}Mg^{12}$ (p, p_3 n_4) $^{18}Ne^{10}$.**
  - **Converter technology cannot be used; the beam hits directly the magnesium oxide target.**
  - **Production rate for ^{18}Ne is ~ $1x10^{12}$ ions/s (dc) for ~200 kW on target.**
  - **^{19}Ne can be produced with one order of magnitude higher intensity but the half-life is 17 seconds!**

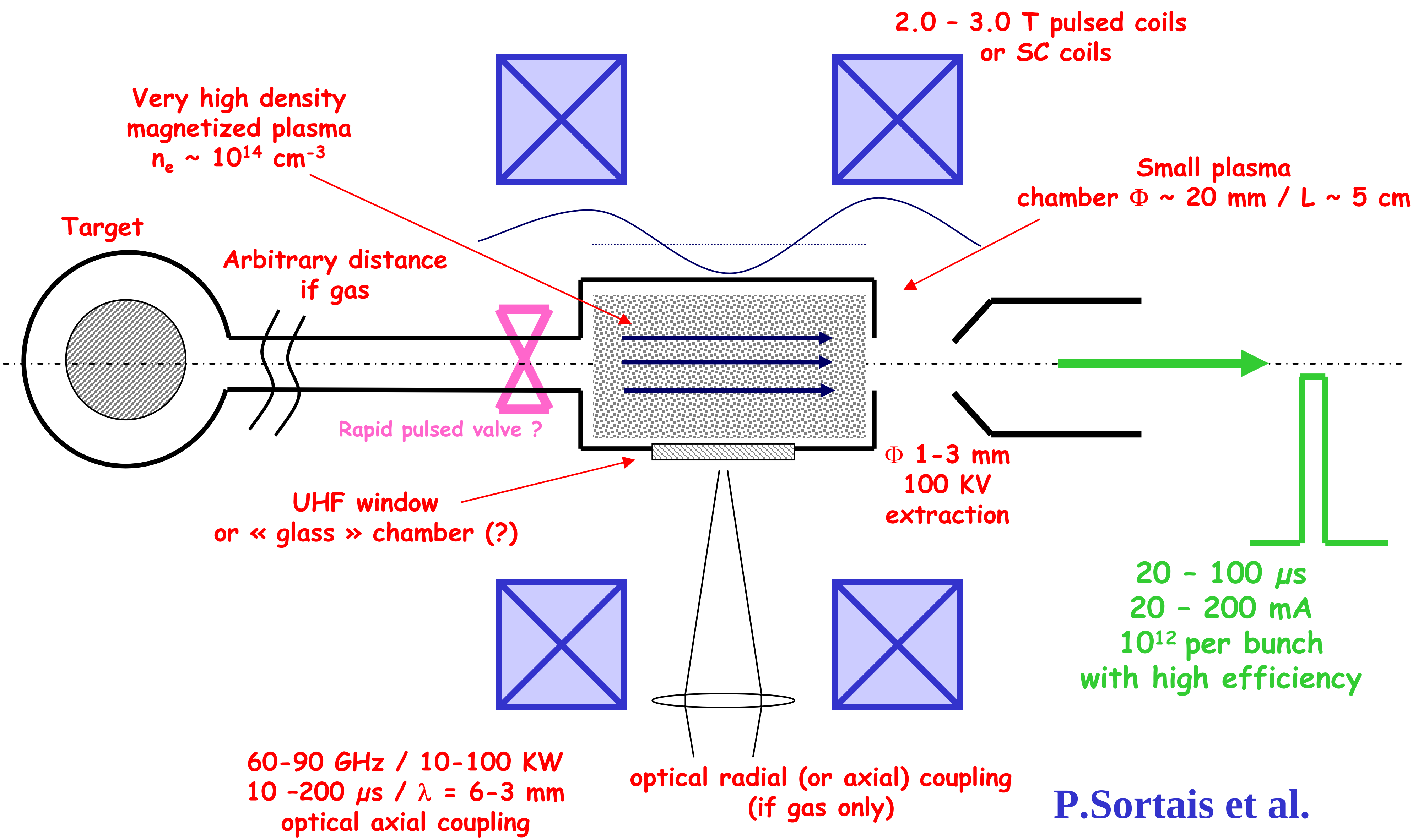
Producing 18Ne and 6He at 100 MeV

- Work within EURISOL task 2 to investigate production rate with "medical cyclotron"
  - Louvain-La-Neuve, M. Loislet



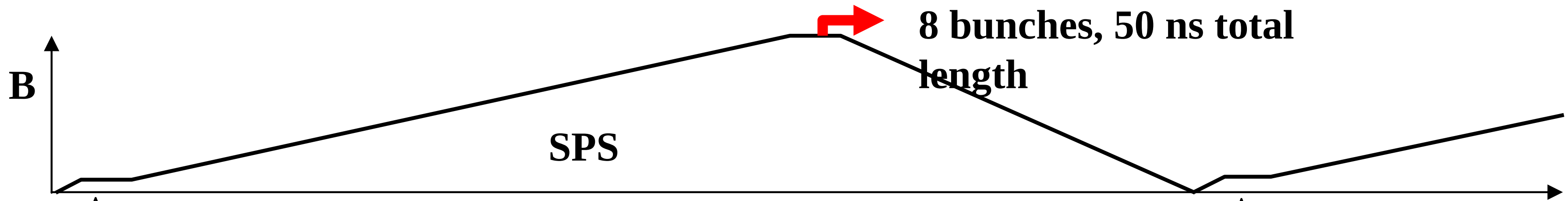


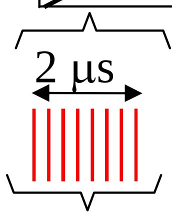
60 GHz « ECR Duoplasmatron » for gaseous RIB

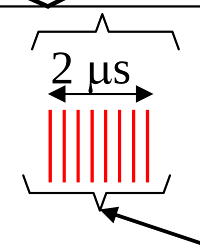


P.Sortais et al.

From dc to very short bunches







SPS: injection of 8 bunches from PS.
Acceleration to decay ring energy and ejection.

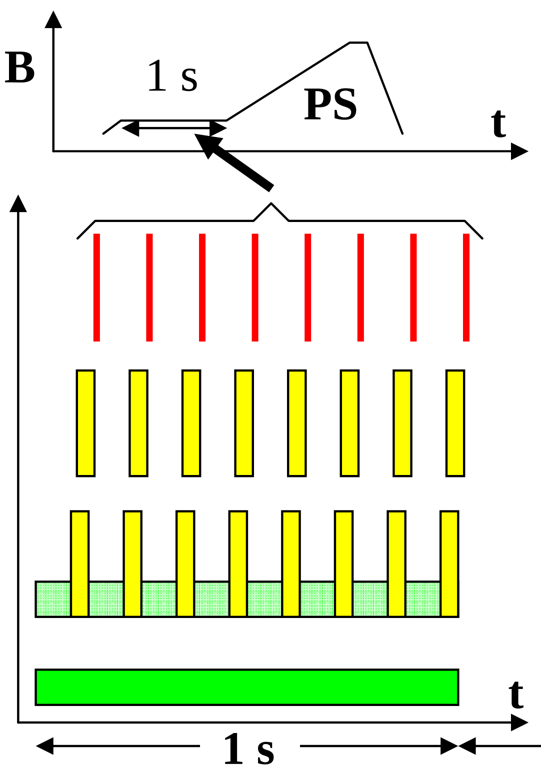
PS: 1 s flat bottom with 16 injections. Acceleration in ~1 s to ~86.7 Tm..

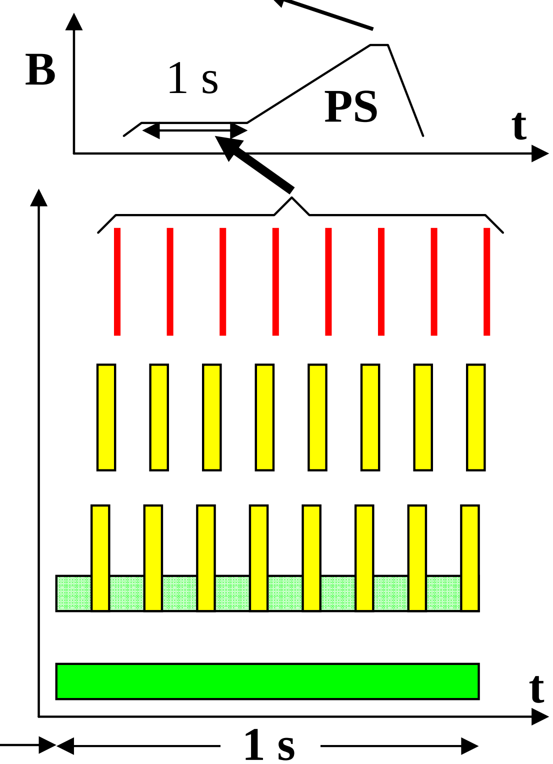
RCS: further bunching to ~100 ns
Acceleration to ~ 8 Tm.
16 repetitions during 1 s.

Post accelerator linac:
acceleration to ~100 MeV/u.
16 repetitions during 1 s.

60 GHz ECR: accumulation for 1/16 s ejection of fully stripped ~50 μs pulse.
16 batches during 1 s.

Target: dc production during 1 s.





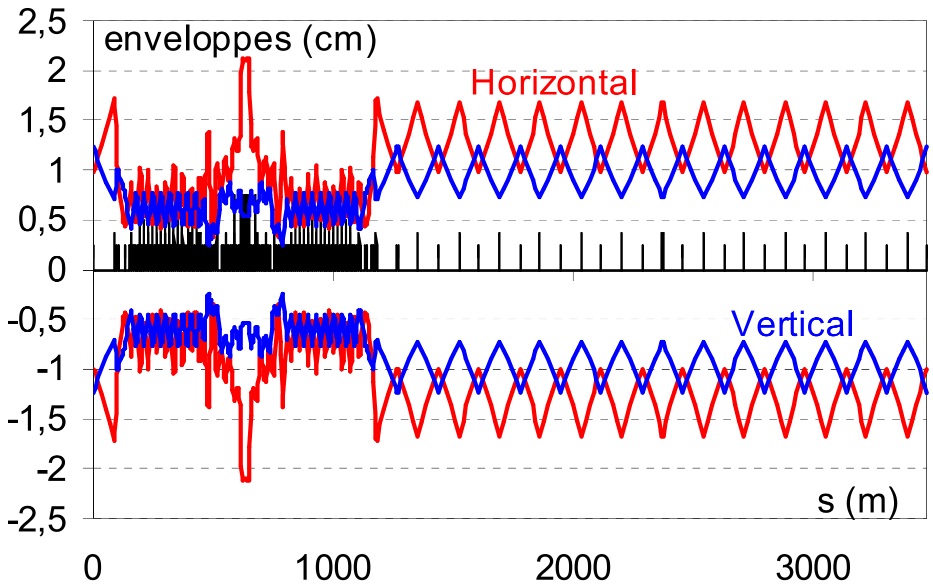
7 s

Decay ring design aspects

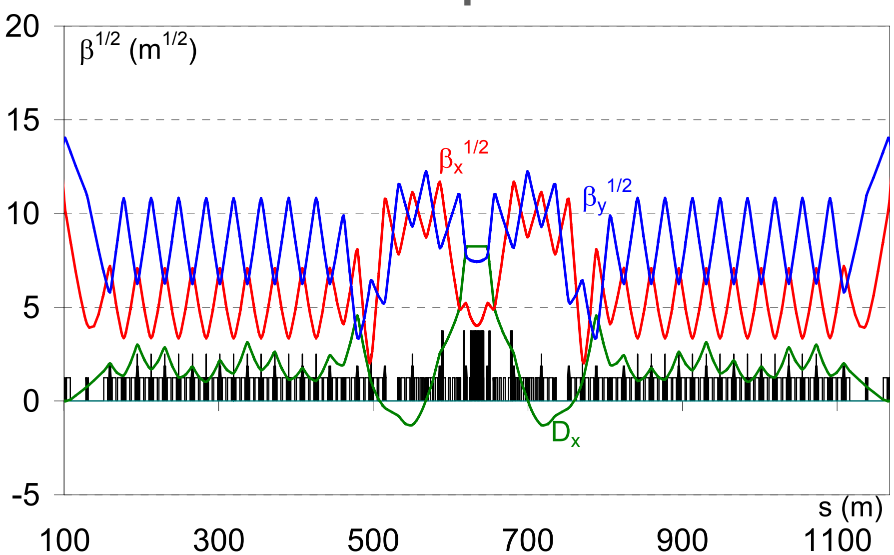
- **The ions have to be concentrated in a few very short bunches**
  - **Suppression of atmospheric background via time structure.**
- **There is an essential need for stacking in the decay ring**
  - **Not enough flux from source and injector chain.**
  - **Lifetime is an order of magnitude larger than injector cycling (120 s compared with 8 s SPS cycle).**
  - **Need to stack for at least 10 to 15 injector cycles.**
- **Cooling is not an option for the stacking process**
  - **Electron cooling is excluded because of the high electron beam energy and, in any case, the cooling time is far too long.**
  - **Stochastic cooling is excluded by the high bunch intensities.**
- **Stacking without cooling "conflicts" with Liouville**

Ring optics

Beam envelopes



Arc optics



In the straight sections, we use FODO cells. The apertures are ±2 cm in the both plans

The arc is a 2π insertion composed of regular cells and an insertion for the injection.

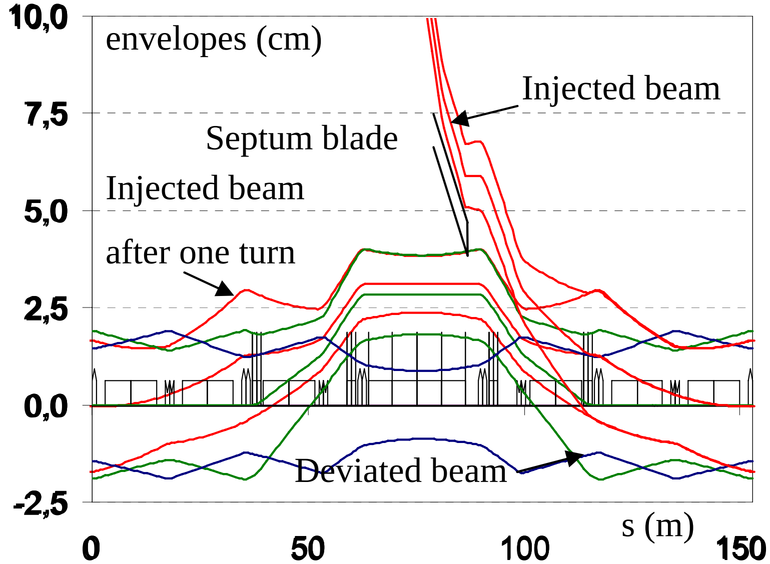
There are 489 m of 6 T bends with a 5 cm half-aperture.

At the injection point, dispersion is as high as possible (8.25 m) while the horizontal beta function is as low as possible (21.2 m).

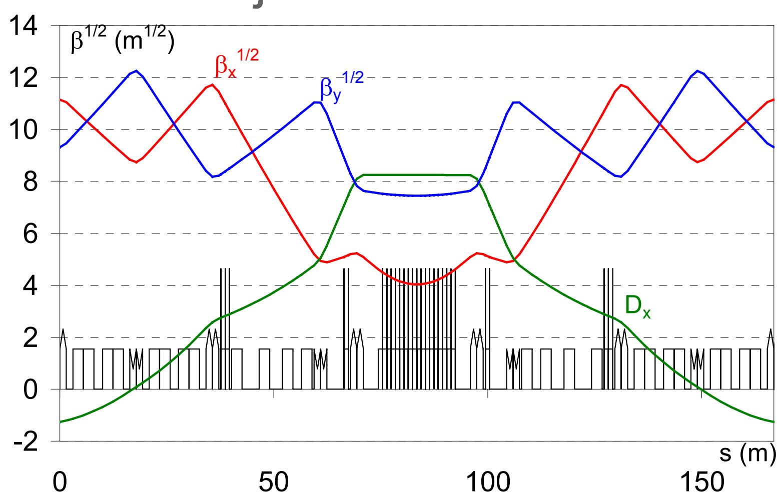
The injection septum is 18 m long with a 1 T field.

Injection

Horizontal envelopes at injection



Optical functions in the injection section



- Injection is located in a dispersive area
- The stored beam is pushed near the septum blade with 4 “kickers”. At each injection, a part of the beam is lost in the septum
- Fresh beam is injected off momentum on its chromatic orbit. “Kickers” are switched off before injected beam comes back
- During the first turn, the injected beam stays on its chromatic orbit and passes near the septum blade
- Injection energy depends on the distance between the deviated stored beam and the fresh beam axis

Parameters of the magnetic elements in the ring

The half-aperture chosen for the magnetic elements is 5 cm

The field calculations are for Helium (except for extraction septum)

	$^{6}He^{2+}$	$^{18}Ne^{10+}$
γ	100	100
Bρ (T.m)	931	559

max QP in the injection section			
	L (m)	K (m-2)	B (T)
IQP4	3	-0,017	-0,80
QP family in the arc FODO cells			
	L (m)	K (m-2)	B (T)
QP1	3	-0,018	-0,84
QP2	3	0,027	1,26
QP family in the straight sections			
	L (m)	K (m-2)	B (T)
DQP1	1	-0,011	-0,53
DQP2	1	0,012	0,54

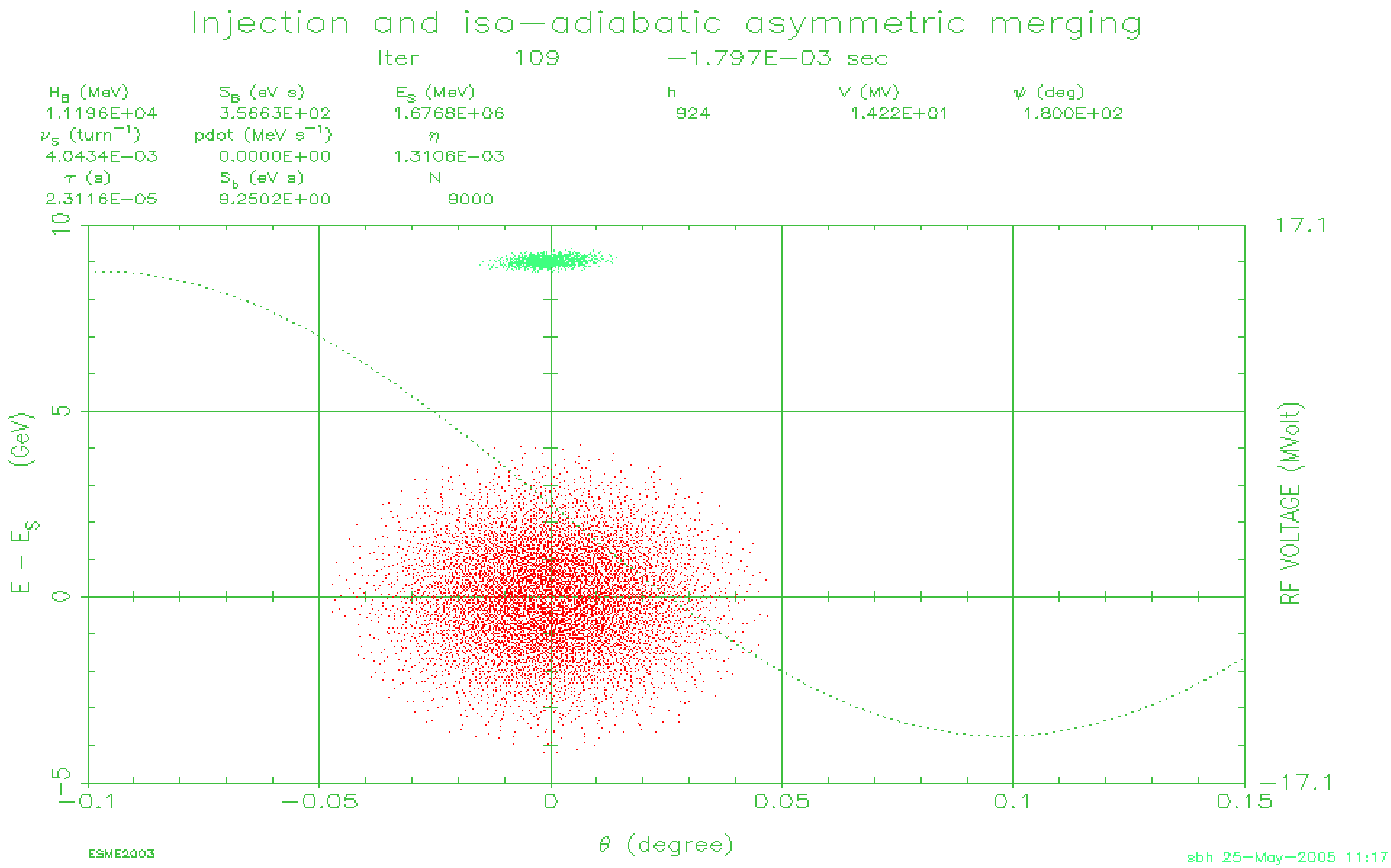
Bends and septa in the ring			
	Length (m)	radius (m)	field (T)
B1	4,89	156	5,98
inj sept	18	931	1
ext sept	22.5	1035	0.6

Injection kickers			
	Length (m)	Deviation (mrad)	BL (T.m)
IKI1	2	0,563	0,524
IKI2	1	-0,16	-0,149

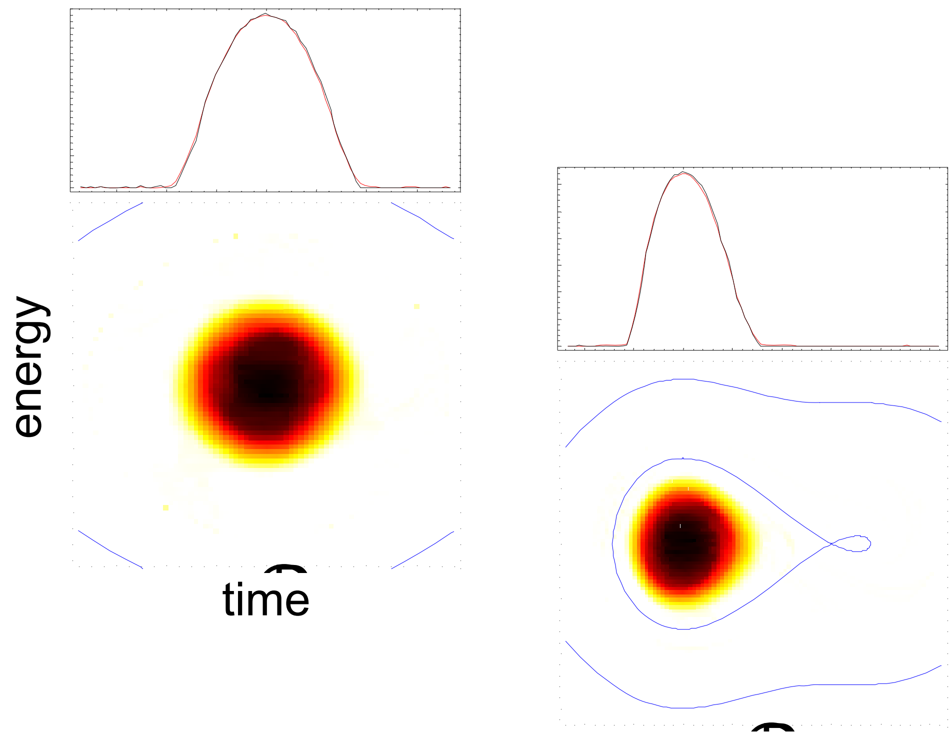
Asymmetric bunch pair merging

- Moves a fresh dense bunch into the core of the much larger stack and pushes less dense phase space areas to larger amplitudes until these are cut by the momentum collimation system.
- Central density is increased with minimal emittance dilution.
- Requirements:
  - Dual harmonic rf system. The decay ring will be equipped with 40 and 80 MHz systems (to give required bunch length of ~10 ns for physics).
  - Incoming bunch needs to be positioned in adjacent rf "bucket" to the stack (i.e., ~10 ns separation!).

Simulation (in the SPS)

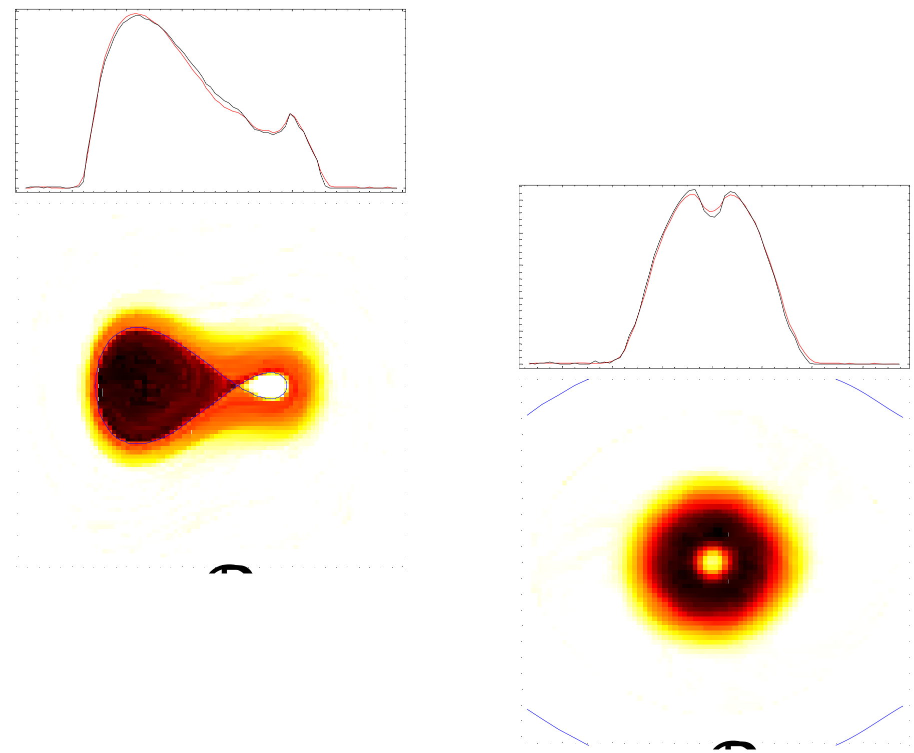


Test experiment in CERN PS



Ingredients

- h=8 and h=16 systems of PS.
- Phase and voltage variations.

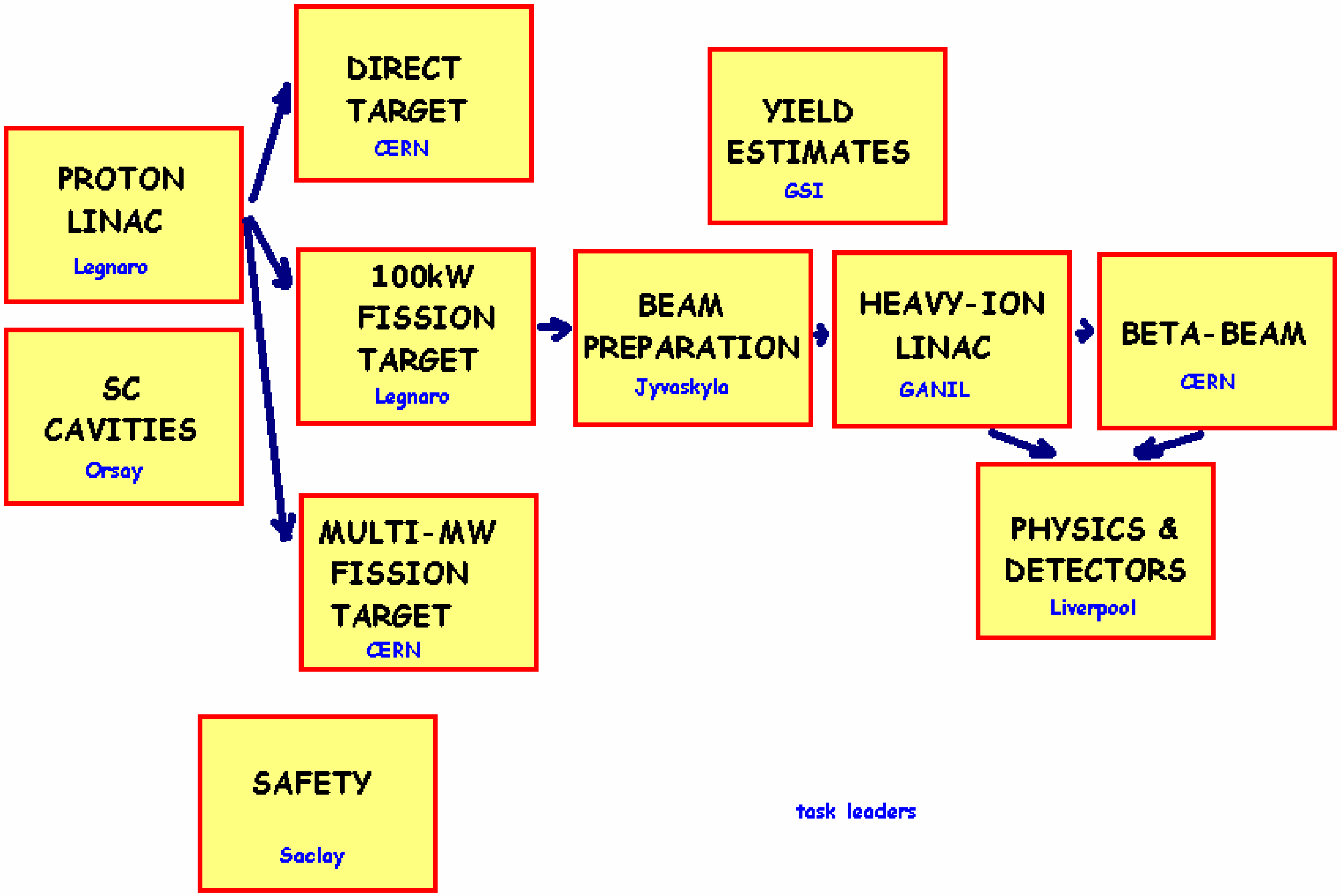


S. Hancock, M. Benedikt and J-L.Vallet, *A proof of principle of asymmetric bunch pair merging*, AB-Note-2003-080 MD

Beta-beam R&D

- **The EURISOL Project**
  - **Design of an ISOL type (nuclear physics) facility.**
  - **Performance three orders of magnitude above existing facilities.**
  - **A first feasibility / conceptual design study was done within FP5.**
  - **Strong synergies with the low-energy part of the beta-beam:**
    - **Ion production (proton driver, high power targets).**
    - **Beam preparation (cleaning, ionization, bunching).**
    - **First stage acceleration (post accelerator ~100 MeV/u).**
    - **Radiation protection and safety issues.**
- **Subtasks within beta-beam task**
  - **ST 1: Design of the low-energy ring(s).**
  - **ST 2: Ion acceleration in PS/SPS and required upgrades of the existing machines including new designs to eventually replace PS/SPS.**
  - **ST 3: Design of the high-energy decay ring.**
  - **Around 38 (13 from EU) man-years for beta-beam R&D over next 4 years (only within beta-beam task, not including linked tasks).**

EURISOL



Peter Butler

Design study objectives

- Establish the limits of the first study based on existing CERN accelerators (PS and SPS)
- Freeze target values for annual rate at the EURISOL beta-beam facility
  - Close cooperation with nowg
- Freeze a baseline for the EURISOL beta-beam facility
- Produce a Conceptual Design Report (CDR) for the EURISOL beta-beam facility
- Produce a first cost estimate for the facility

Challenges for the study

- Production
- Charge state distribution after ECR source
- The self-imposed requirement to re-use a maximum of existing infrastructure
  - Cycling time, aperture limitations etc.
- The small duty factor
- The activation from decay losses
- The high intensity ion bunches in the accelerator chain and decay ring

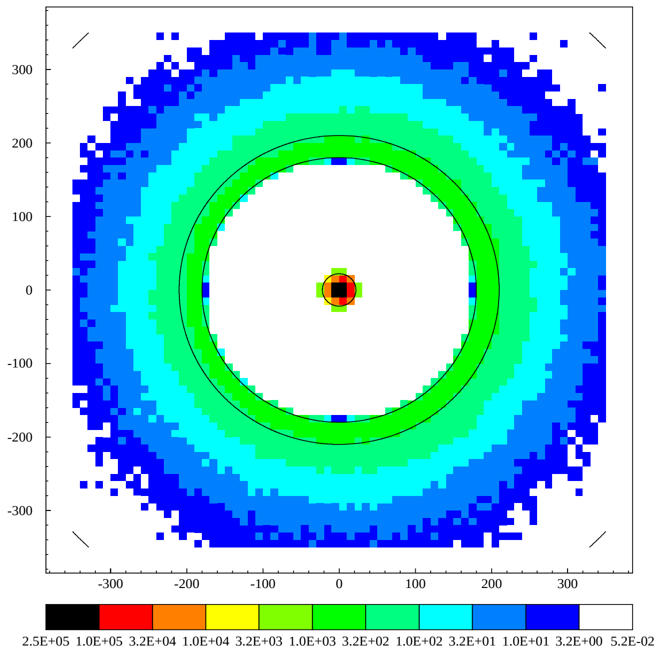
Duty factor

- A small duty factor does not only require short bunches in the decay ring but also in the accelerator chain
  - Space charge limitations

Decay losses

- **Losses during acceleration**
  - **Full FLUKA simulations in progress for all stages (M. Magistris and M. Silari, *Parameters of radiological interest for a beta-beam decay ring*, TIS-2003-017-RP-TN).**

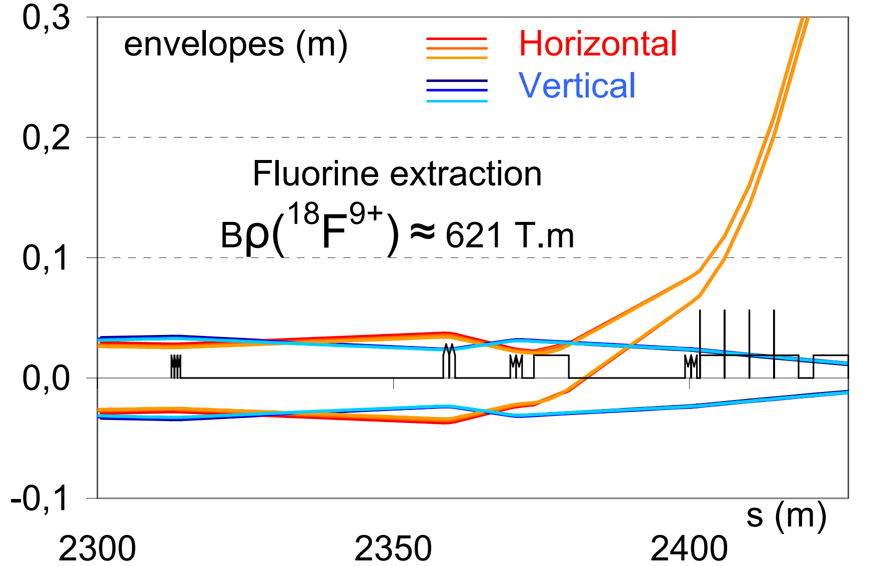
- **Preliminary results:**
  - **Manageable in low-energy part.**
  - **PS heavily activated (1 s flat bottom).**
    - **Collimation? New machine?**
  - **SPS ok.**
  - **Decay ring losses:**
    - **Tritium and sodium production in rock is well below national limits.**
    - **Reasonable requirements for tunnel wall thickness to enable decommissioning of the tunnel and fixation of tritium and sodium.**
    - **Heat load should be ok for superconductor.**



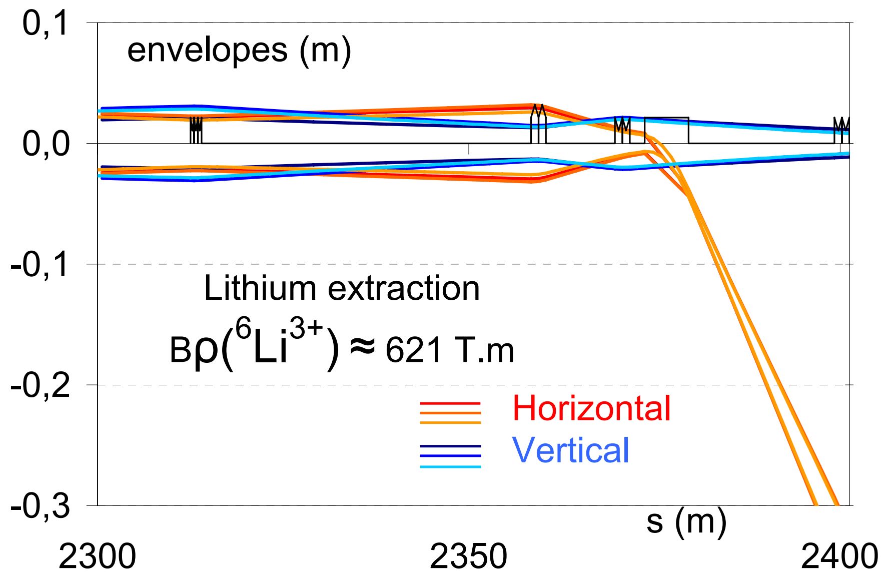
FLUKA simulated losses in surrounding rock (no public health implications)

Decay products extraction

Fluorine extraction



Lithium extraction



Two free straight sections after the first arc dipole enable the extraction of decay products coming from long straight sections.

The decay product envelopes are plotted for disintegrations at the begin, the middle and the end of the straight section.

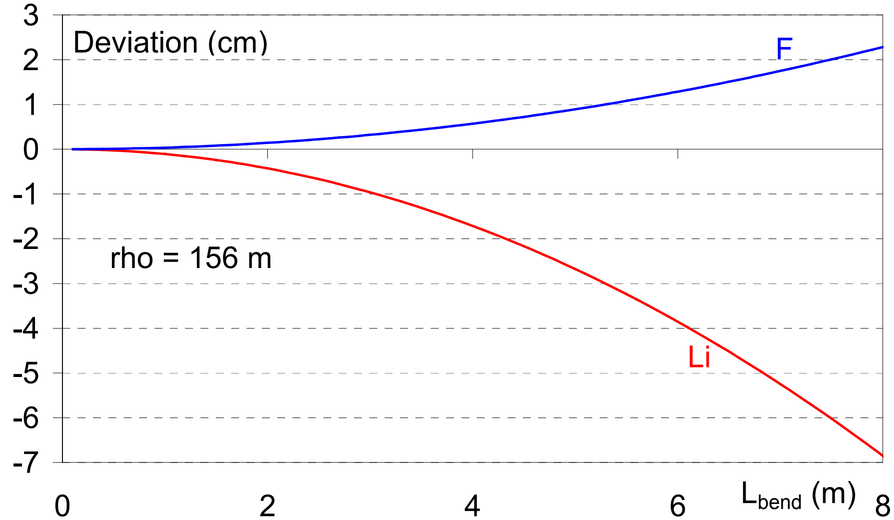
Fluorine extraction needs an additional septum.

The permanent septum for Fluorine extraction is 22.5 m long and its field is 0.6 T.

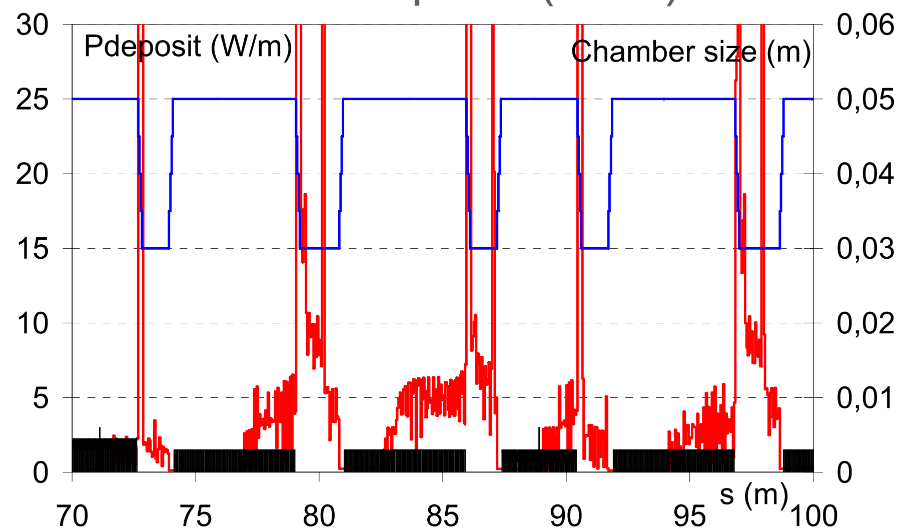
Lithium extraction can be made without a septum.

Decay products deposit in the arc

Deviation of one decay product by one bend as a function of its length



Lithium deposit (W/m)



The dispersion after a L long bend with a radius equal to ρ is :

$$D = \rho\left(1 - \cos\left(\frac{L}{\rho}\right)\right)$$

By this way, we can evaluate the maximum length of a bend before the decay products are lost there.

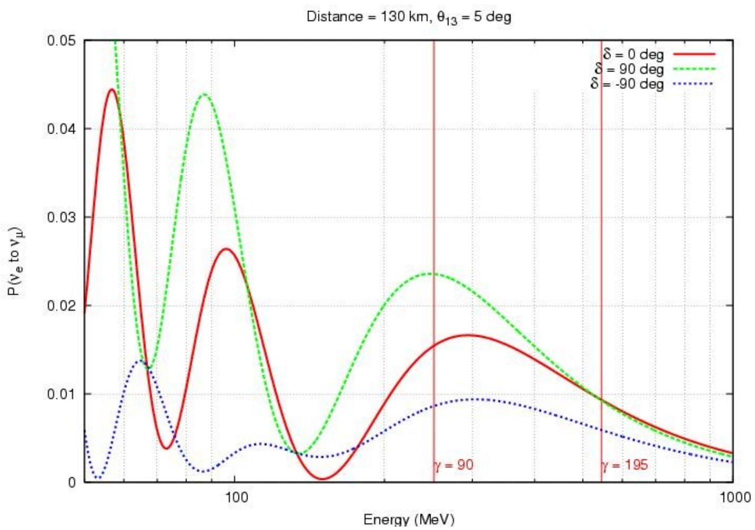
If we choose a 5 cm half aperture, half of the beam is lost for a 7 m long bend. With a 5 m long bend, there is very low deposits in the magnetic elements.

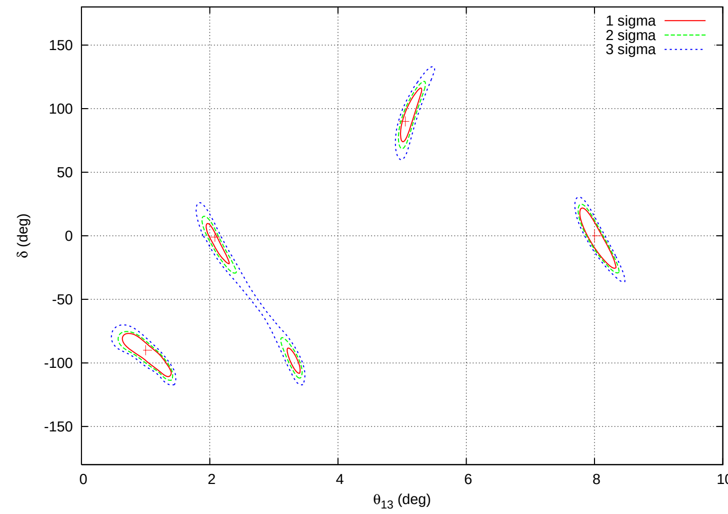
Only the Lithium deposit is problematic because the Neon intensity is far below the Helium one.

Production

- Target design and gas transport forms part of EURISOL DS target task
  - Alternative direct production at low energy with "medical cyclotron" at 100 MeV studied at LNL
- The production target values are challenging but not unrealistic

EC: A monochromatic neutrino beam





Decay	$T_{1/2}$	BR_ν	EC/ν	I^{β}_{EC}	B(GT)	E_{GR}	Γ_{GR}	Q_{EC}	E_ν	ΔE_ν
$^{148}Dy \rightarrow {}^{148}Tb^*$	3.1 m	1	0.96	0.96	0.46	620		2682	2062	
$^{150}Dy \rightarrow {}^{150}Tb^*$	7.2 m	0.64	1	1	0.32	397		1794	1397	
$^{152}Tm2^- \rightarrow {}^{152}E_T^*$	8.0 s	1	0.45	0.50	0.48	4300	520	8700	4400	520
$^{150}Ho2^- \rightarrow {}^{150}Dy^*$	72 s	1	0.77	0.56	0.25	4400	400	7400	3000	400

^{150}Dy

- Partly stripped ions: The loss due to stripping smaller than 5% per minute in the decay ring
- Possible to produce 1 10^{11} ^{150}Dy atoms/second (1+) with 50 microAmps proton beam with existing technology (TRIUMF)
- An annual rate of 10^{18} decays along one straight section seems as a realistic target value for a design study
- Beyond EURISOL DS: Who will do the design?
- Is ^{150}Dy the best isotope?

Conclusions

- **Beta-Beam Task well integrated in the EURISOL DS**
- **EURISOL study will result in a first conceptual design report for a beta-beam facility at CERN.**
  - **We need a "STUDY 1" for the beta-beam to be considered a credible alternative to super beams and neutrino factories**
- **The annual rate of version 1 for the Beta-beam baseline does not match the earlier quoted target values**
  - **We have a lot of work ahead of us, see talk in nowg**
  - **We need a "green-field" study to establish true physics potential of the beta-beam concept (and cost).**
- Recent new ideas promise a fascinating continuation into further developments beyond the ongoing EURISOL DS
  - Low energy beta-beam, EC beta-beam, High gamma beta-beam, etc.