A BASELINE BETA-BEAM

Mats Lindroos
AB Department, CERN

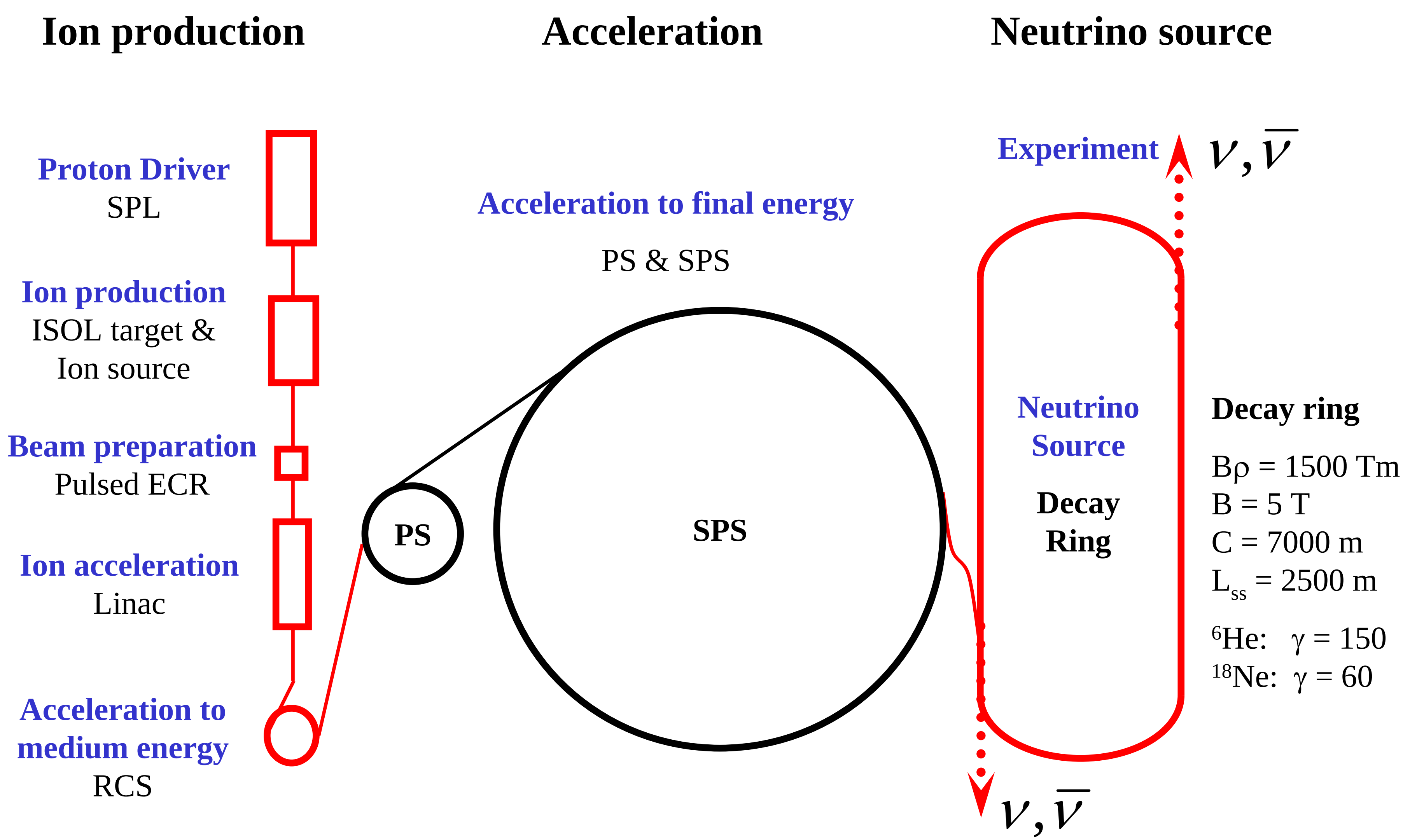
on behalf of the
Beta-beam Study Group

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

Outline

- **Beta-beam baseline design**
  - **A baseline scenario, ion choice, main parameters**
  - **Ion production**
  - **Decay ring design issues**
  - **Asymmetric bunch merging for stacking in the decay ring**
- **The EURISOL DS**
- **Mathematica as a tool in accelerator physics**
  - **Trend curves to define interesting parameter space for design effort**
- **Conclusions**

Beta-beam “first study 2002”



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:** ${}^{6}_{2}He \rightarrow {}^{6}_{3}Li\ e^{-}\ \overline{\nu}$

    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

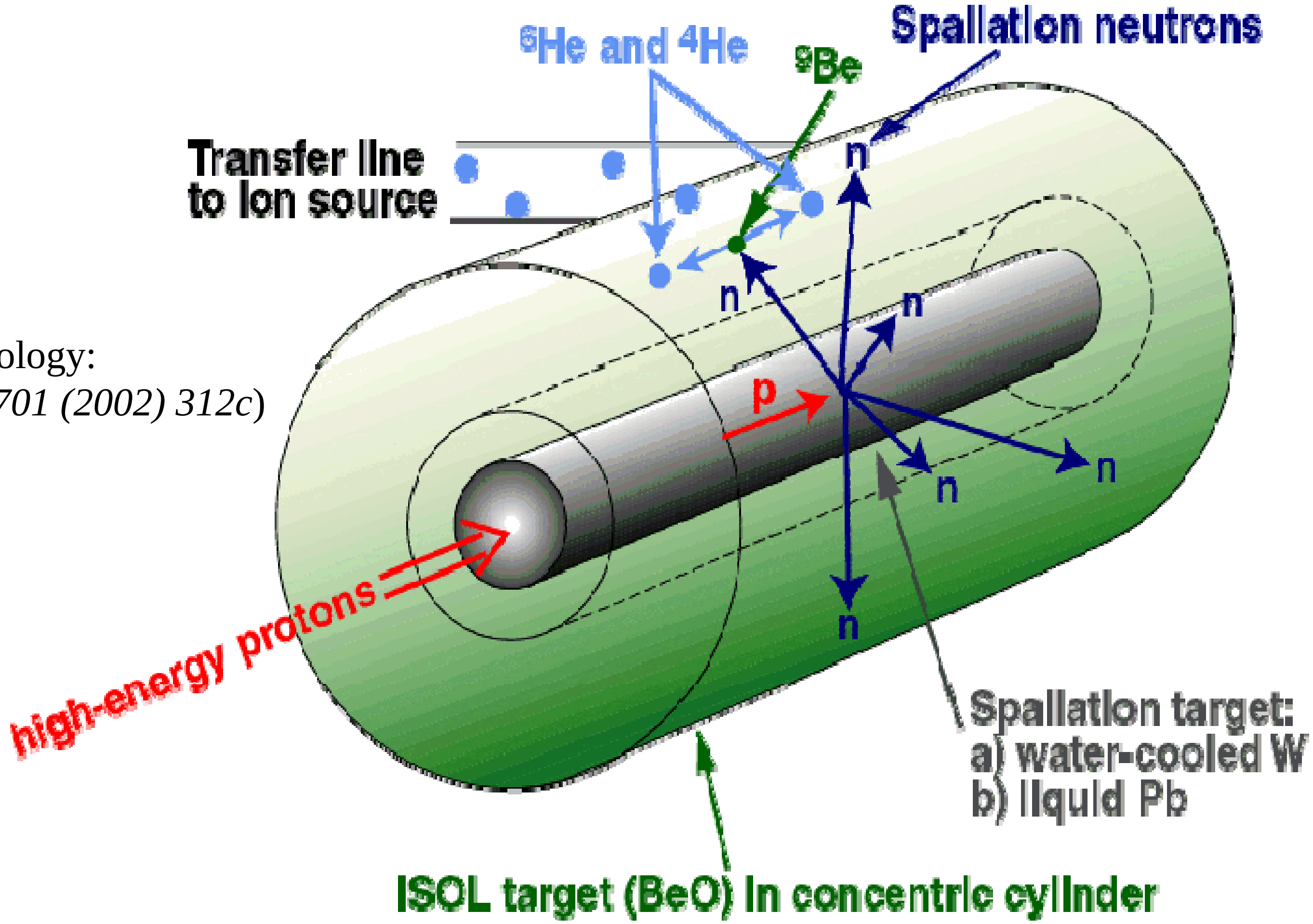
- The first study "Beta-beam" was aiming for:
  - A beta-beam facility that will run for a "normalized" year of 10^7 seconds
  - An annual rate of 2.9 10^{18} anti-neutrinos (^6He) and 1.1 10^{18} neutrinos (^{18}Ne) at γ=100

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 is for anti-neutrinos 29 10^{18} and for neutrinos 11 10^{18} in ten years running

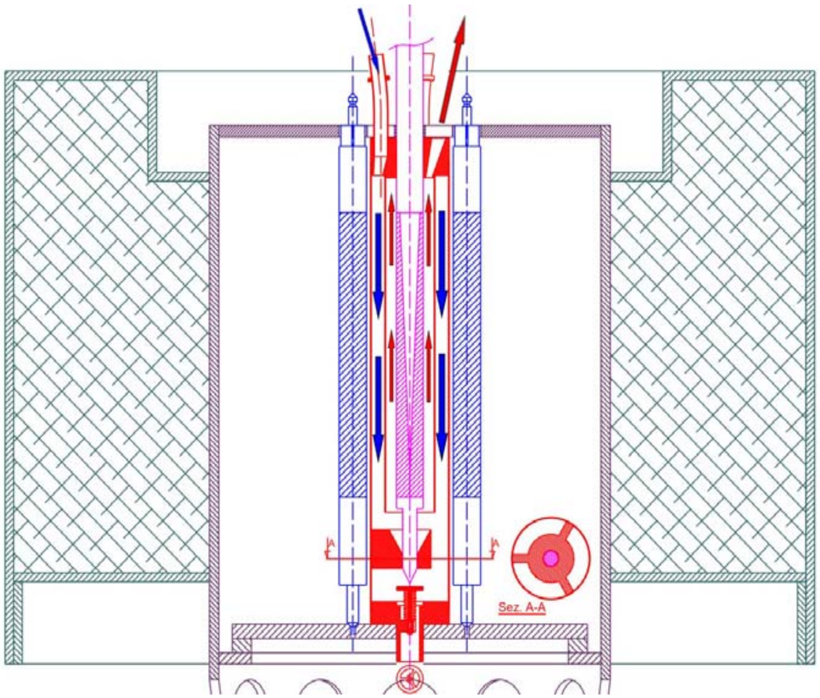
^{6}He production from ^{9}Be(n,α)

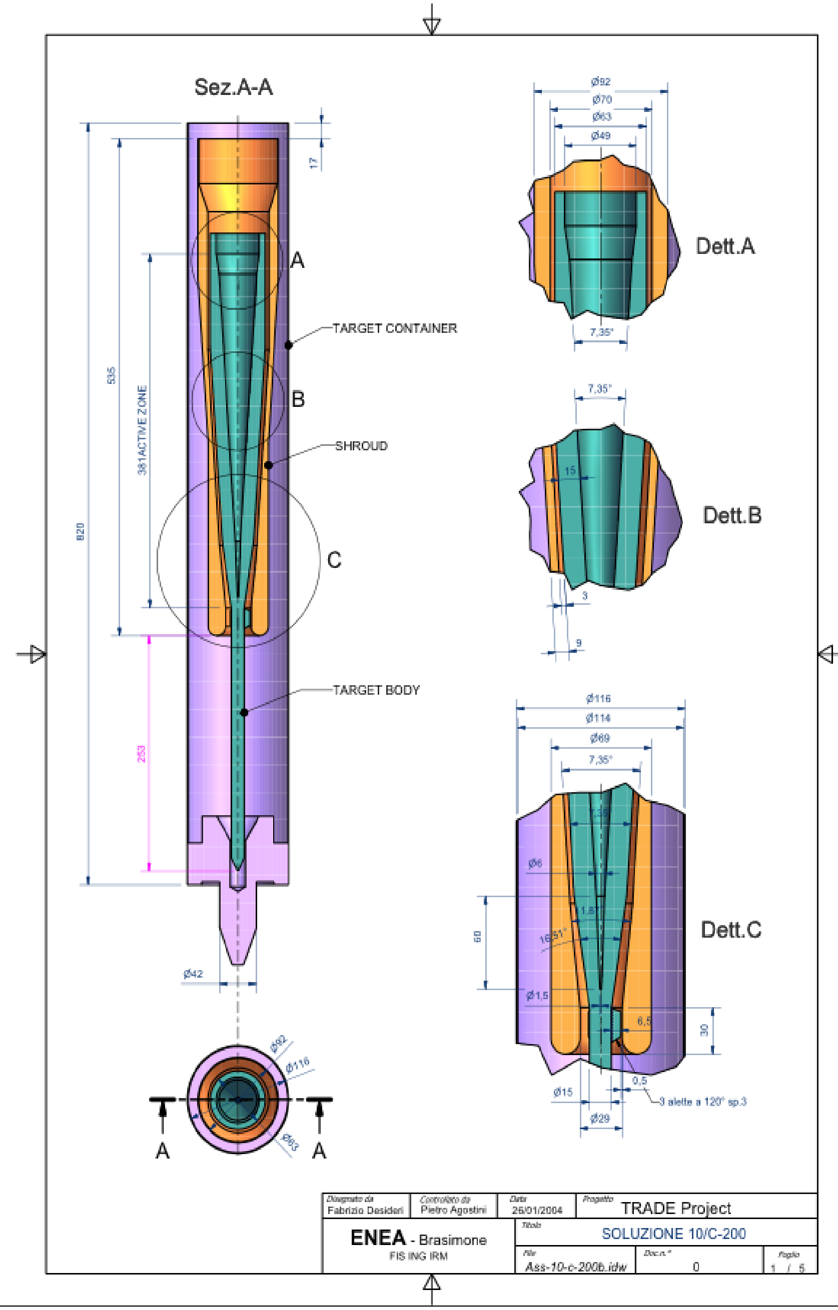


Converter technology:
(*J. Nolen, NPA 701 (2002) 312c*)

- **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.**

The Spallation Target System





The inner geometry is characterized by three conical cavities having different angles and total length equal to the active height of the TRIGA core. The cone tip (lowest cone) is exposed to the highest power density for two reasons:

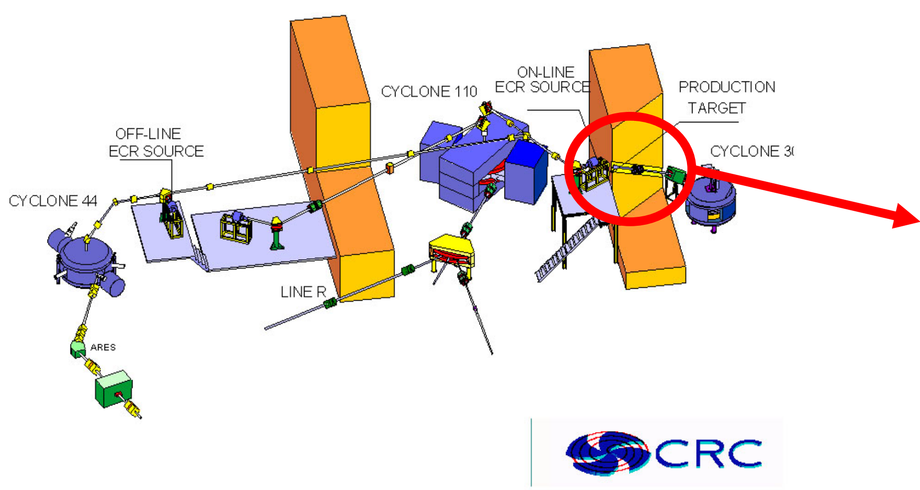
- the relevant proton current at the centre of the Gaussian distribution,
- the forward scattering of protons as a consequence of the conical angle steepness.

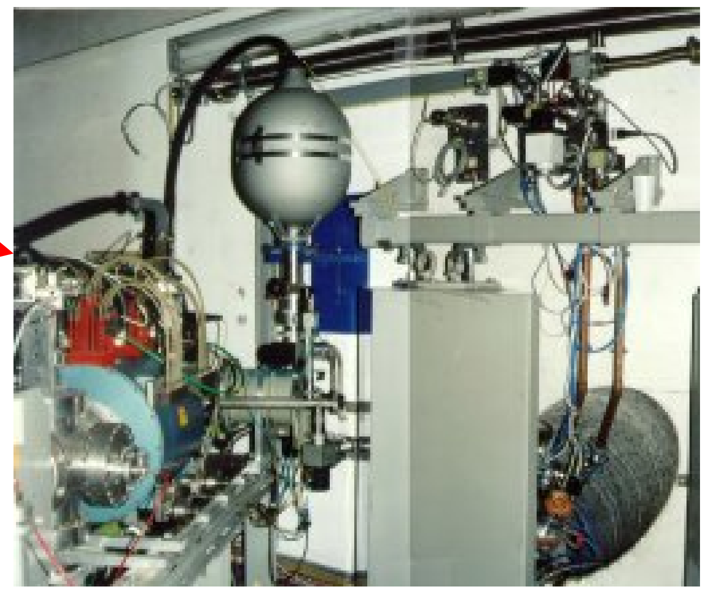
^{18}Ne production

- **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!**

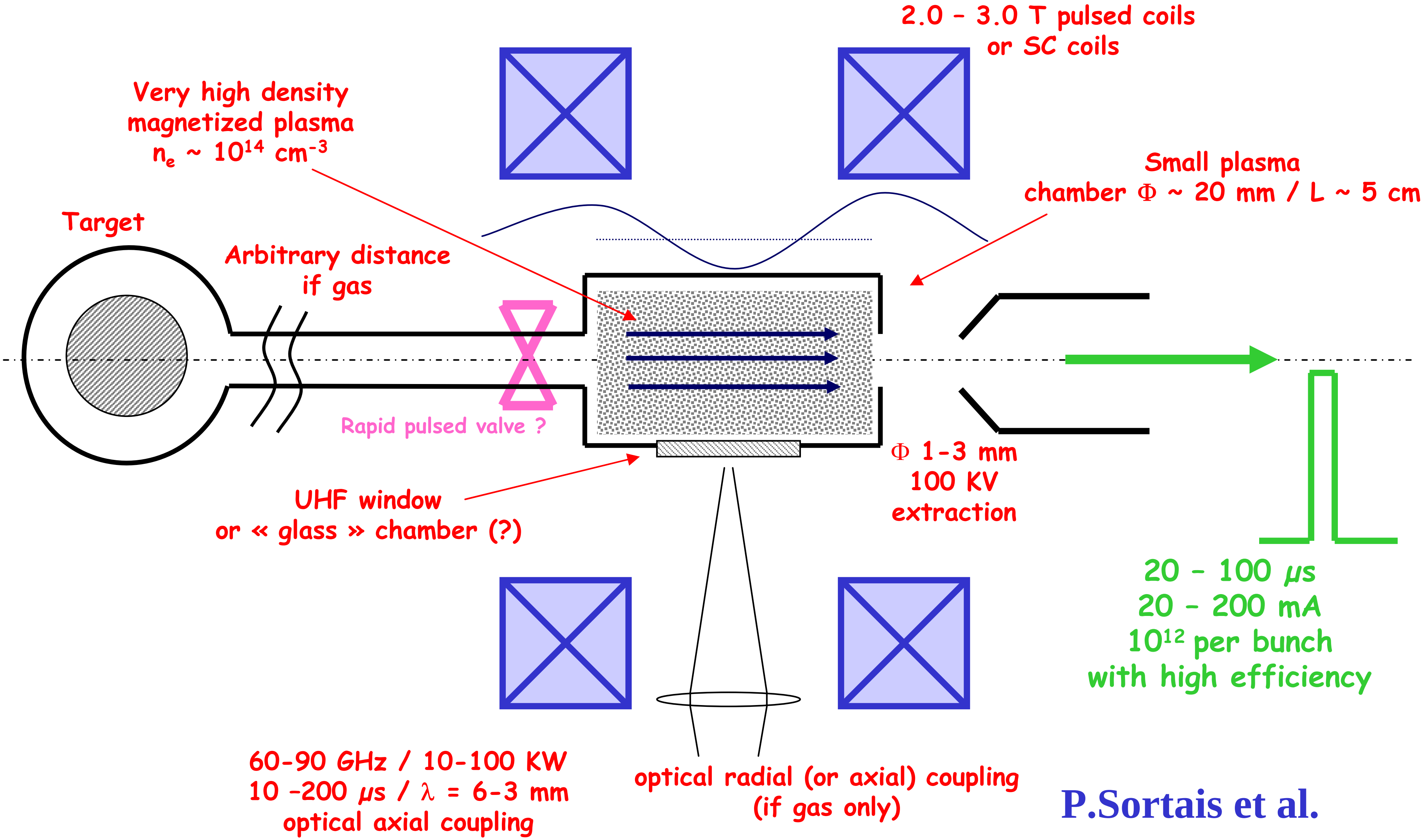
Producing ^{18}Ne and ^{6}He at 100 MeV

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



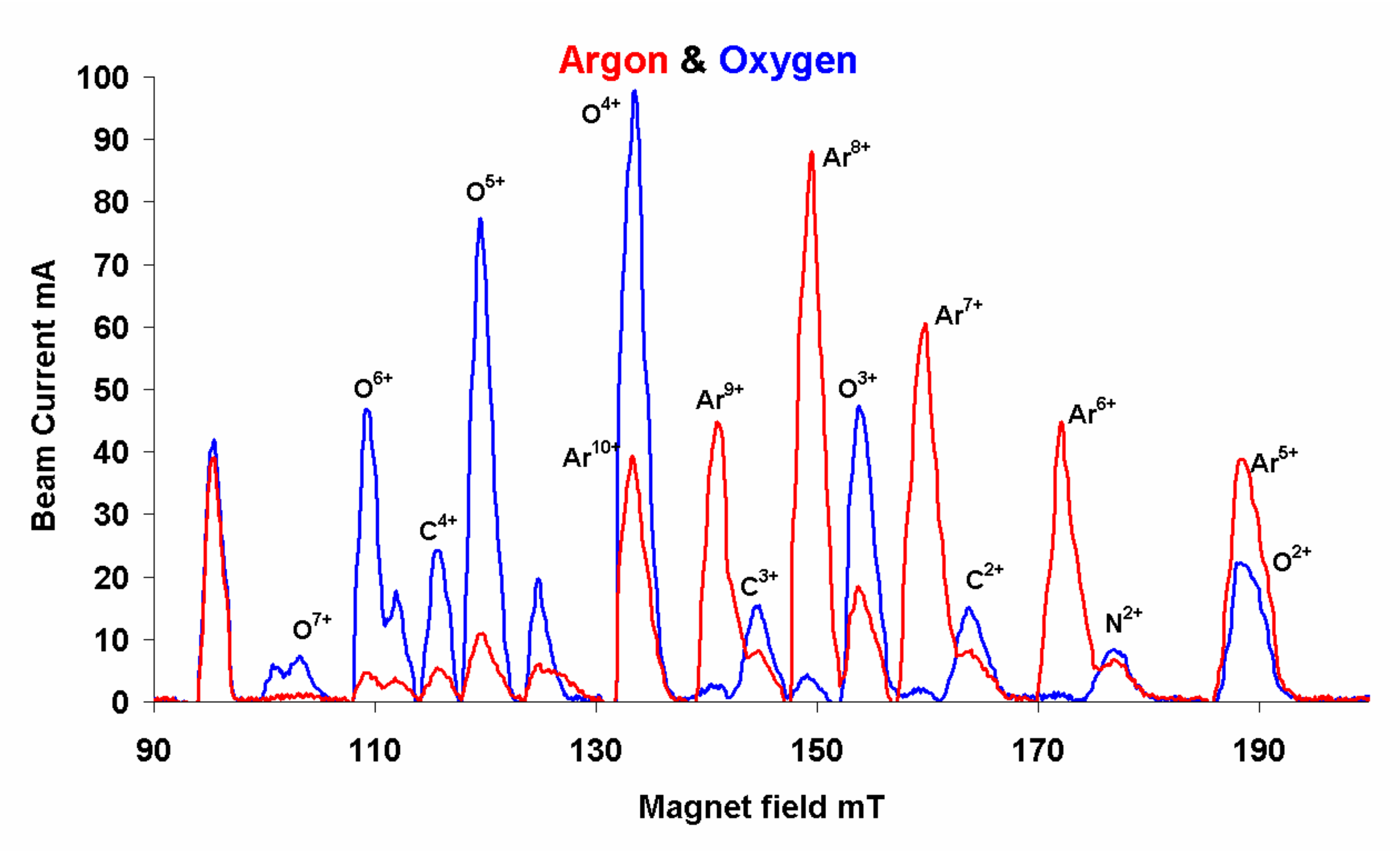


60 GHz « ECR Duoplasmatron » for gaseous RIB

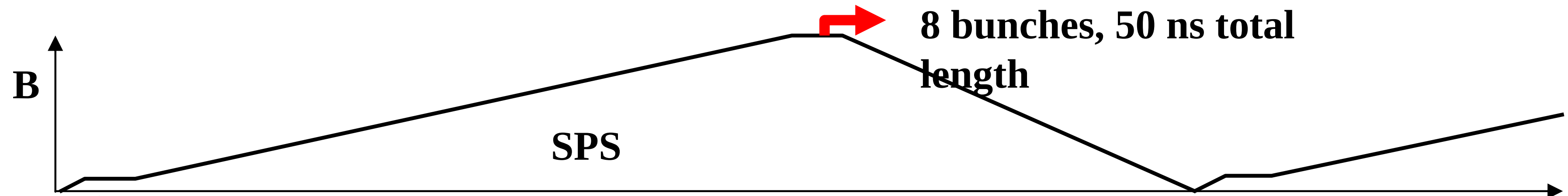


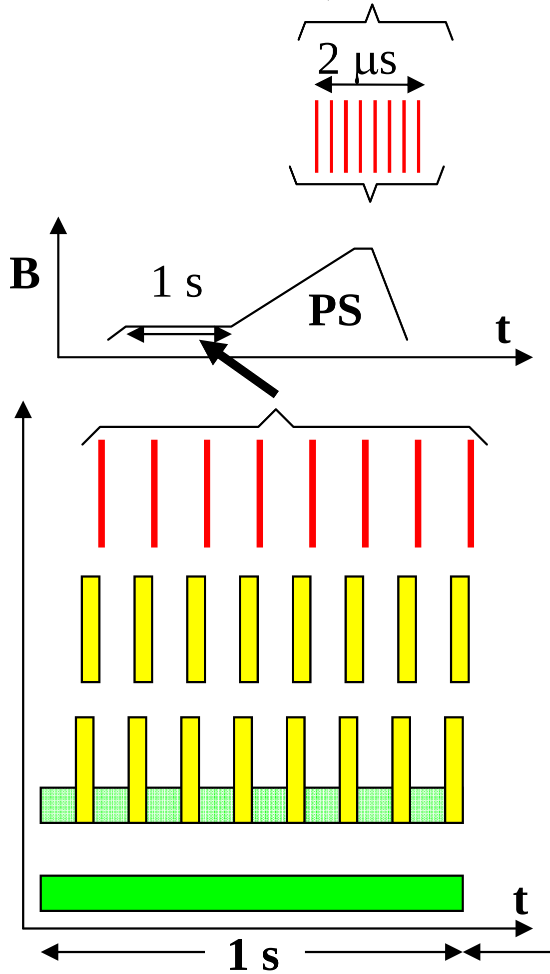
P.Sortais et al.

Charge state distribution!



From dc to very short bunches Version 1





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..

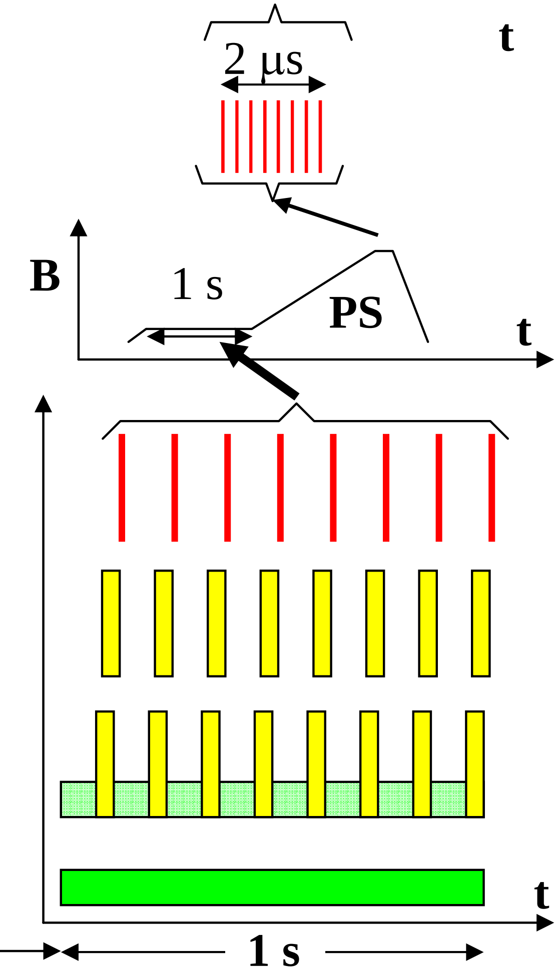
RCS: further bunching to ~100 ns
Acceleration to ~ 8 Tm.
16 repetitions during 1 s.

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



Intensities, 6He, v1

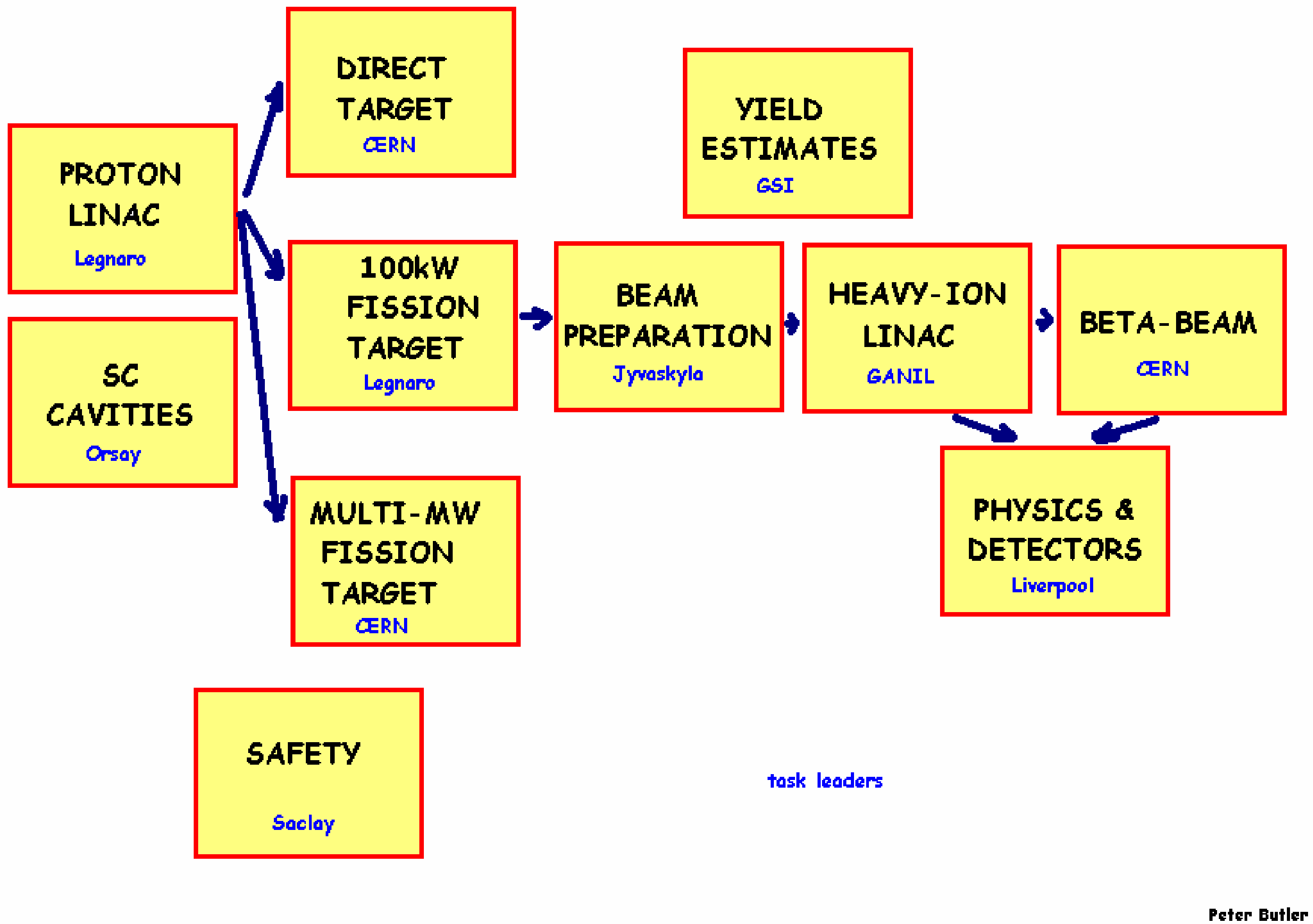
Machine	Total Intensity out (10^{12})	Comment
Source	20	DC pulse, Ions extracted for 1 second
ECR	1.16934	Ions accumulated for 60 ms, 99% of all 6He ions in highest charge state, 50 microseconds pulse length
RCS inj	0.582144	Multi-turn injection with 50% efficiency
RCS	0.570254	Acceleration in 1/32 seconds to top magnetic rigidity of 8 Tm
PS inj	6.82254	Accumulation of 16 bunches during 1 second
PS	5.75908	Acceleration in 0.8 seconds to top magnetic rigidity of 86.7 Tm and merging to 8 bunches.
SPS	5.43662	Acceleration to gamma=100 in 2.54 seconds and ejection to decay ring of all 8 bunches (total cycle time 6 seconds)
Decay ring	58.1137	Total intensity in 8 bunches of 50/8 ns length each at gamma=100 will result in a duty cycle of 0.0022. Maximum number of merges = 15.

Intensities, 18Ne, v1

Machine	Total Intensity out (10^{10})	Comment
Source	80	DC pulse, Ions extracted for 1 second
ECR	1.42222	Ions accumulated for 60 ms, 30% of all 18Ne ions in one dominant charge state, 50 microseconds pulse length
RCS inj	0.709635	Multi-turn injection with 50% efficiency
RCS	0.703569	Acceleration in 1/32 seconds to top magnetic rigidity of 8 Tm
PS inj	10.093	Accumulation of 16 bunches during 1 second.
PS	9.57532	Acceleration in 0.8 seconds to top magnetic rigidity of 86.7 Tm and merging to 8 bunches.
SPS	9.45197	Acceleration to gamma=100 in 1.42 seconds and ejection to decay ring of all 8 bunches (total cycle time 3.6 seconds)
Decay ring	277.284	8 bunches of 50/8 ns length each will at gamma=100 result in a duty cycle of 0.0022. Maximum number of merges = 40.

Beta-beam R&D

- **Part of the EURISOL Design Study**
  - **Design Study in the 6th Framework Programme of the EU**
- **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.**

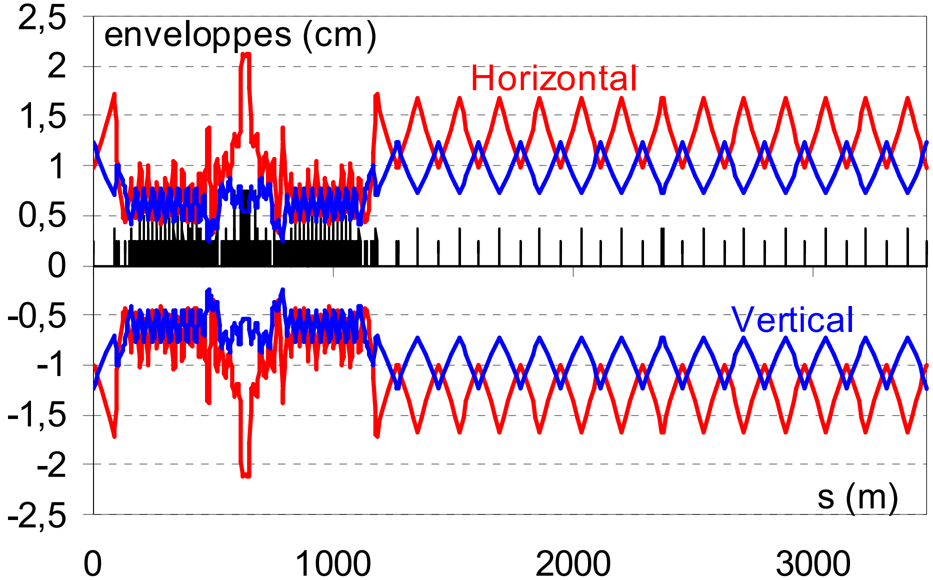

DIRECT TARGET
CERN
PROTON LINAC
Legnaro
YIELD ESTIMATES
GSI
100kW FISSION TARGET
Legnaro
BEAM PREPARATION
Jyvaskyla
HEAVY-ION LINAC
GANIL
BETA-BEAM
CERN
SC CAVITIES
Orsay
MULTI-MW FISSION TARGET
CERN
PHYSICS & DETECTORS
Liverpool
SAFETY
Saclay
task leaders
Peter Butler

Design study objectives

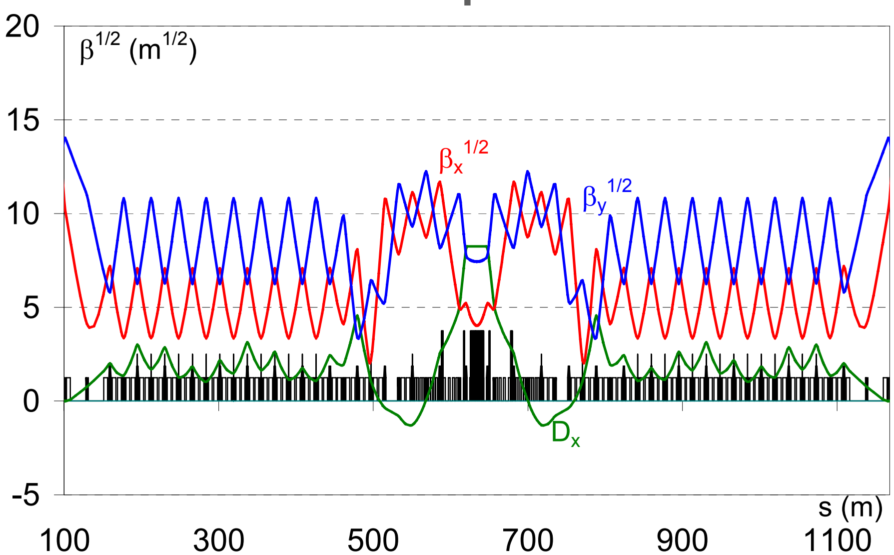
- Establish the limits of the first study based on existing CERN accelerators (PS and SPS)
- Freeze target values for annual rate at the EURISOL beta-beam facility
  - Close cooperation with nowg
- Freeze a baseline for the EURISOL beta-beam facility
- Produce a Conceptual Design Report (CDR) for the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

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.

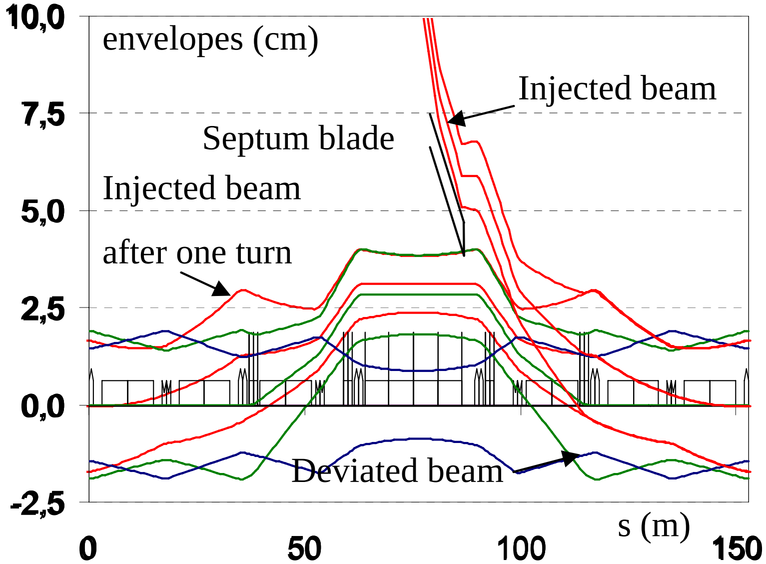
There are 489 m of 6 T bends with a 5 cm half-aperture.

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).

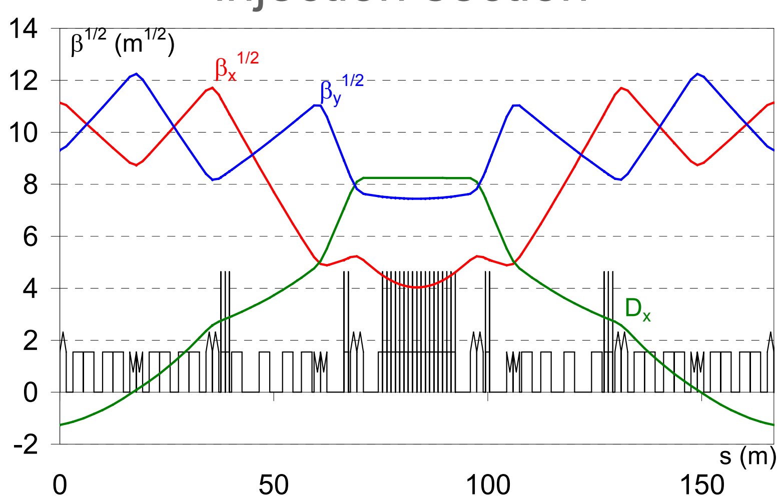
The injection septum is 18 m long with a 1 T field.

Injection

Horizontal envelopes at injection



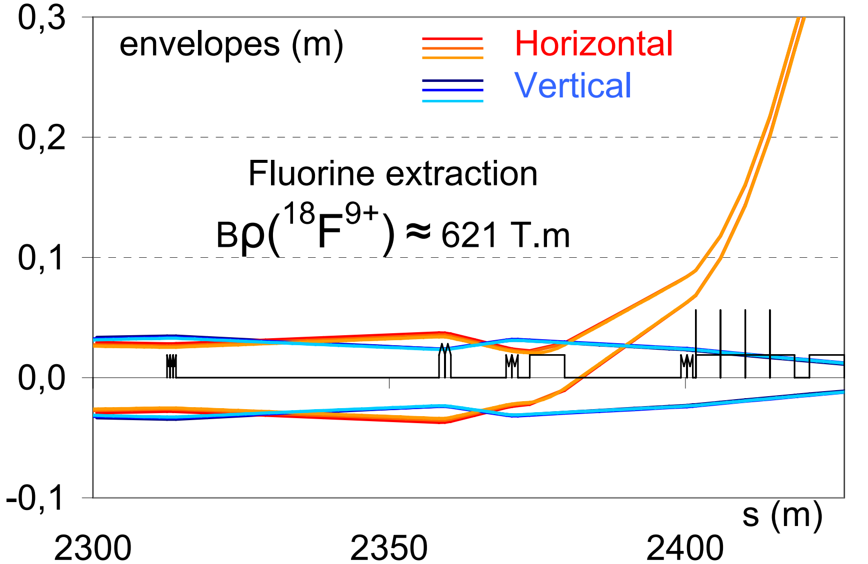
Optical functions in the injection section



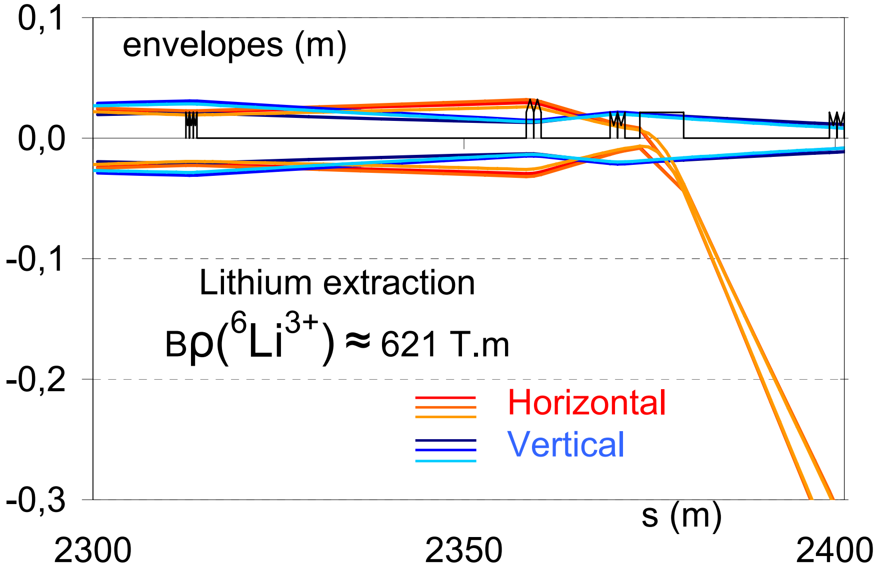
- Injection is located in a dispersive area
- The stored beam is pushed near the septum blade with 4 “kickers”. At each injection, a part of the beam is lost in the septum
- Fresh beam is injected off momentum on its chromatic orbit. “Kickers” are switched off before injected beam comes back
- During 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

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.

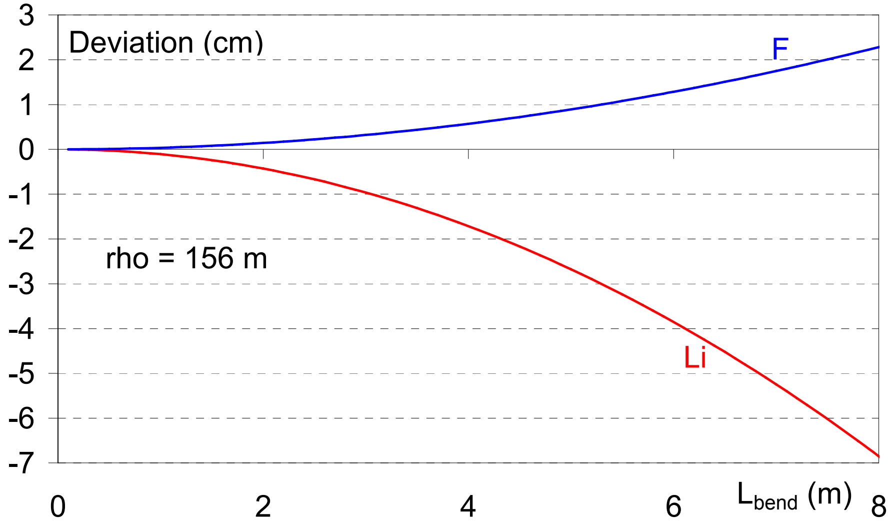
Fluorine extraction needs an additional septum.

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

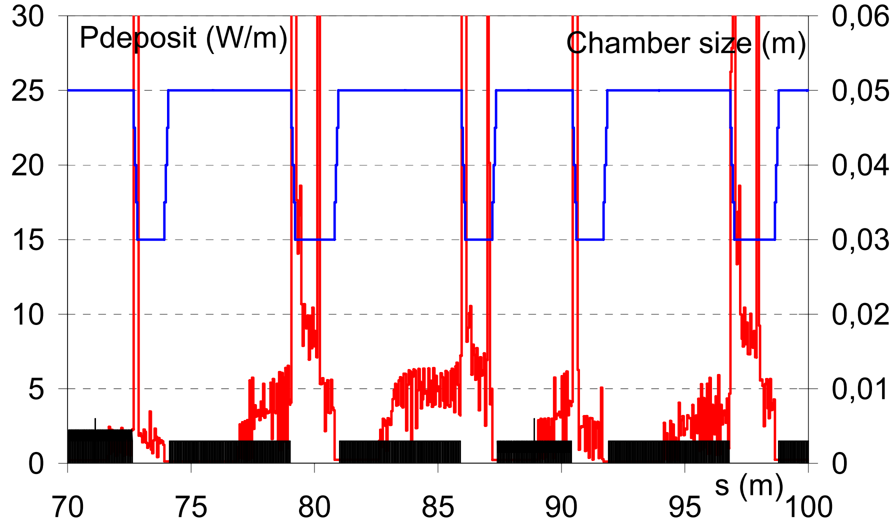
Lithium extraction can be made without a septum.

Decay products deposit in the arc

Deviation of one decay product by one bend in 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.

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
$B\rho$ (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

Challenges for the study

- Production
- ECR efficiency for single charge states
- 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

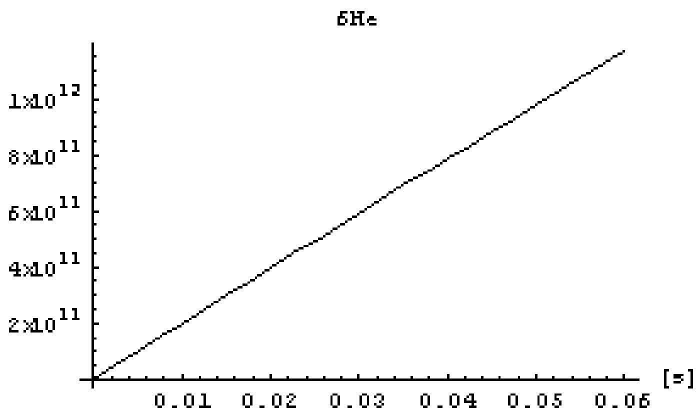
Decay losses, ECR

ECR Accumulation

```
ecraccumulation := (ClearAll[n];
  gamma[t_] := 1 + ecrejTpern / Epern;
  decayrate[t_] := Log[2] n[t] / (gamma[t] thalf);
  eqns = {D[n[t], t] == sourcerate - decayrate[t], n[0]==0};
  n[t_] = ecrefficiency n[t] /. DSolve[eqns, n[t], t] //First;
  nout0 = n[ecraccumulationtime]
)

set6He; ecraccumulation
Plot[n[t], {t, 0,ecraccumulationtime},
  PlotLabel->name, AxesLabel->{"[s]",None}];
```

$1.16971\ 10^{12}$

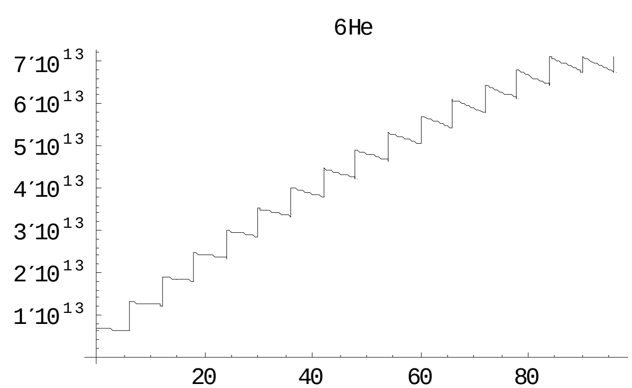


Decay Ring Accumulation

```
decayringaccumulation := (ClearAll[n];
  gamma[t_] := 1 + topTpern / Epern;
  decayrate[t_] := Log[2] n[t] / (gamma[t] thalf);
  eqns = {D[n[t], t] == -decayrate[t], n[0]==nout6};
  nsinglebatch[t_] = n[t] /. DSolve[eqns, n[t], t] //First;
  n[t_] = Sum[UnitStep[t-t0] UnitStep[t0+mergesratio*spsrepetitiontime-t] *
    nsinglebatch[t-t0], {t0, 0,t,spsrepetitiontime}];
  nout7 = n[(mergesratio-1)spsrepetitiontime]
)
fullchain := (spsout; decayringaccumulation)

set6He; fullchain
Plot[n[t], {t, 0,(mergesratio+1)spsrepetitiontime+10^-6},
  PlotPoints->200, PlotLabel->name, AxesLabel->{"[s]",None}];
```

$7.11588 \, 10^{13}$



Number of ions

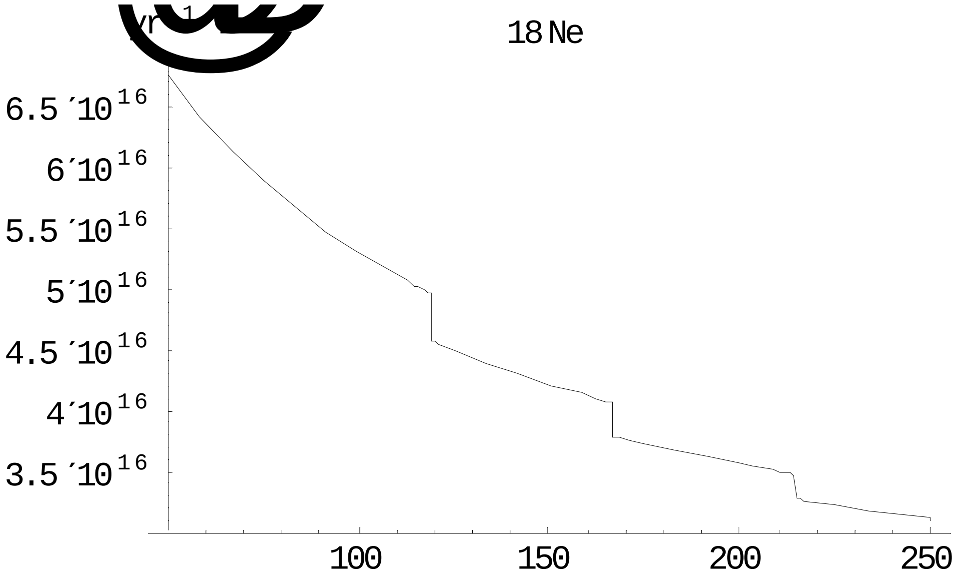
```
set6He; fullchain;
StandardForm[StyleForm[NumberForm[TableForm[
  N[{sourcerate, nout0, nout1, nout2, nout3, nout4, nout6, nout7}],
  TableHeadings->{
    {"Source rate", "ECR", "RCS inj", "RCS", "PS inj", "PS", "SPS", "Decay Ring"},
    None
  }], 3], FontWeight->"Plain", FontSize->16]]
5 annualrate
```

Source rate	$2.\times 10^{13}$
ECR	1.17×10^{12}
RCS inj	5.83×10^{11}
RCS	5.71×10^{11}
PS inj	8.22×10^{12}
PS	7.02×10^{12}
SPS	6.63×10^{12}
Decay Ring	7.12×10^{13}

$1.06841\ 10^{19}$

Gamma dependency

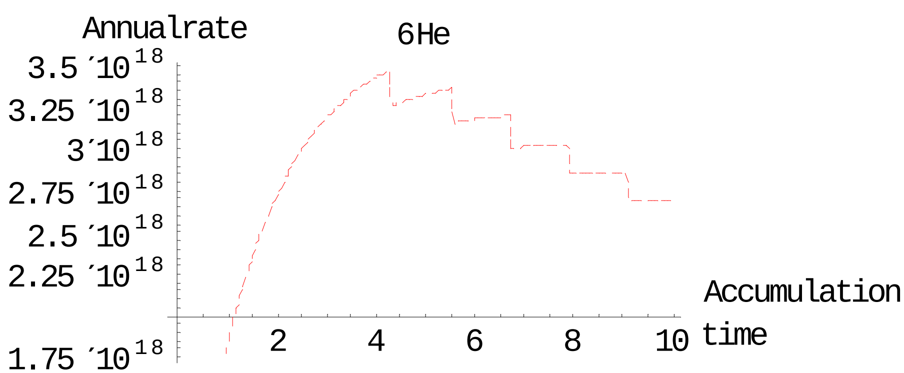
```
set18Ne;
mergesratio := 40 Sqrt[topgamma/100];
Plot[Evaluate[topgamma=x; annualrate], {x, 50,250},
  PlotLabel->name, AxesLabel->{None,DisplayForm[ \(\("[yr"\^"-1"\)"]"\) ]}];
```



Accumulation dependency

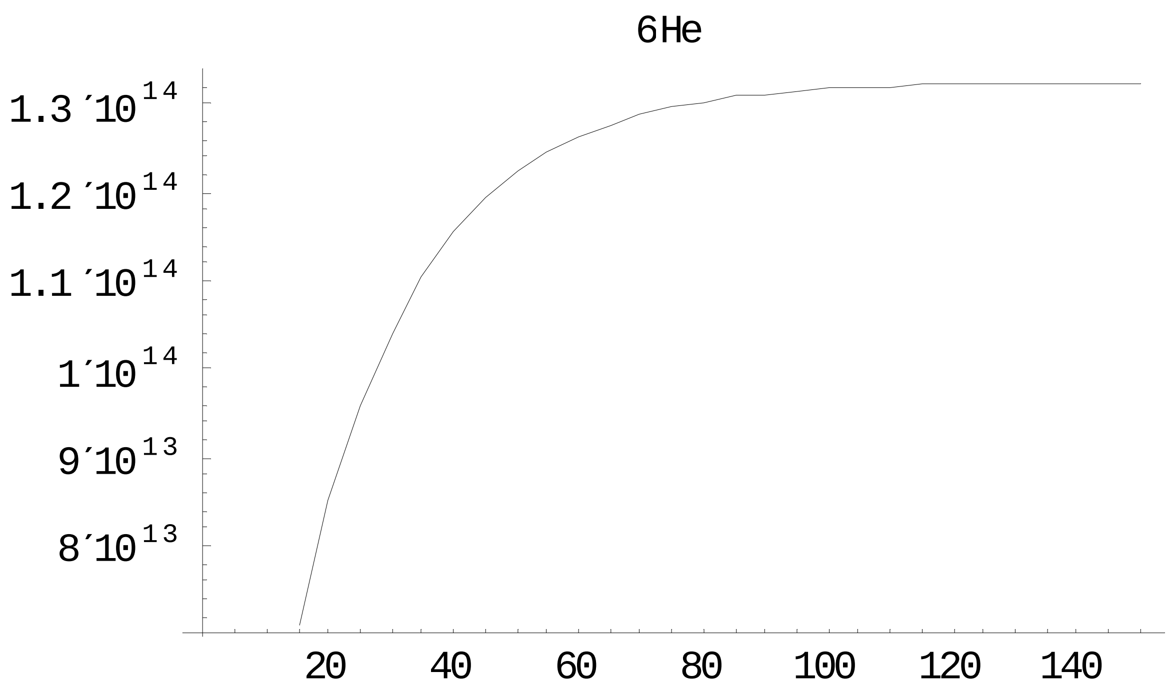
```
set6He;
spscycletime
p1b =
  ListPlot
   Table Evaluate rcsbatches = x;
     p accumulationtime, annualrate      , 160, 1
   PlotJoined ® True, PlotLabel ® "6He"
   PlotStyle ®       1 , Dashing   0.02, 0.01
   AxesLabel ® "Accumulation\ntime", "Annualrate"
```

6.

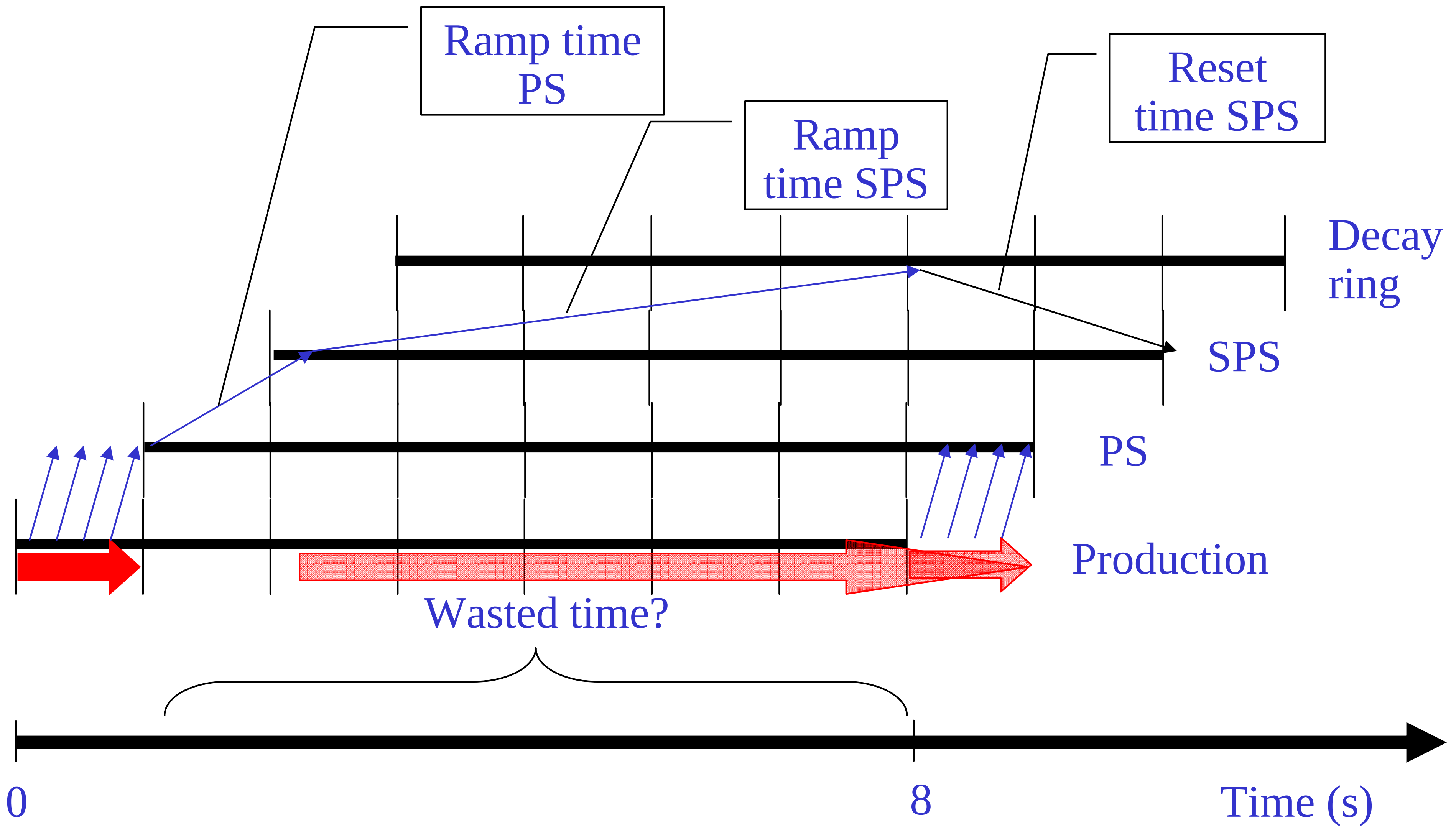


Duty factor dependency

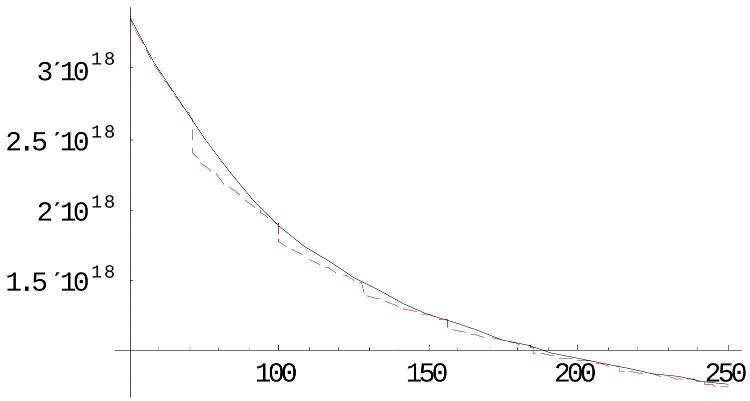
```
set6He;
ListPlot[
  Table[Evaluate[{mergesratio=x, fullchain}], {x, 15,150,5}],
  PlotJoined->True, PlotLabel->name];
```



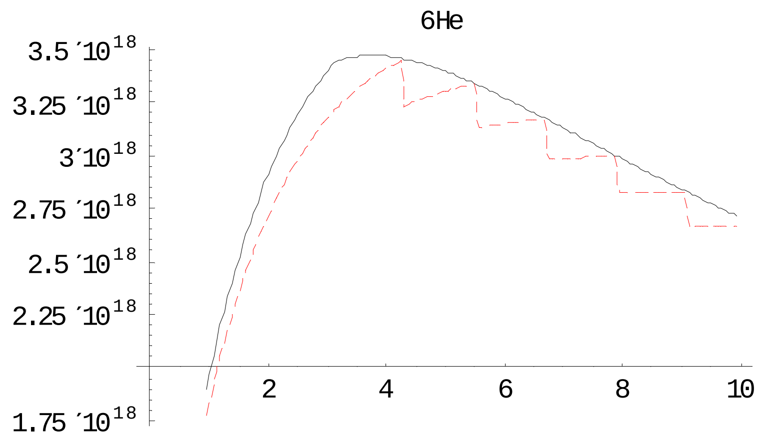
The slow cycling time. What can we do?



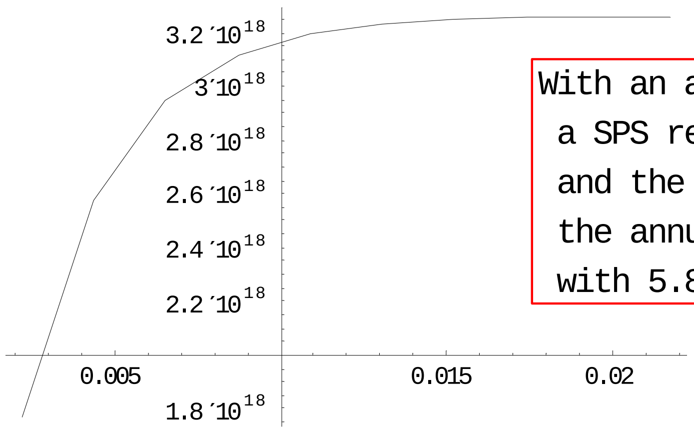
How to change the flux, ^{6}He



Flux as a function of gamma



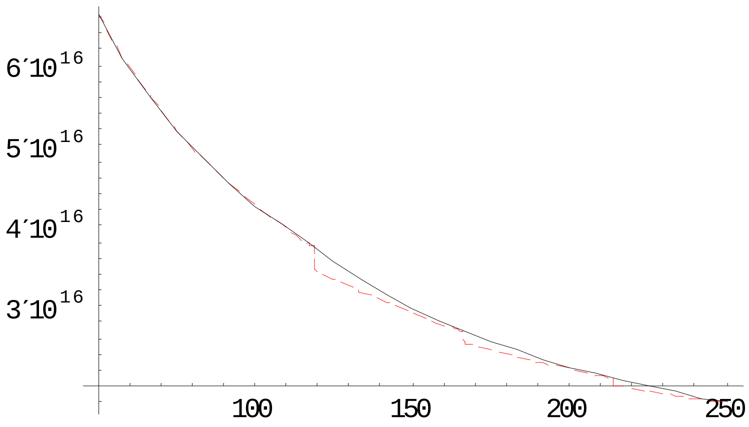
Flux as a function of accumulation time in PS



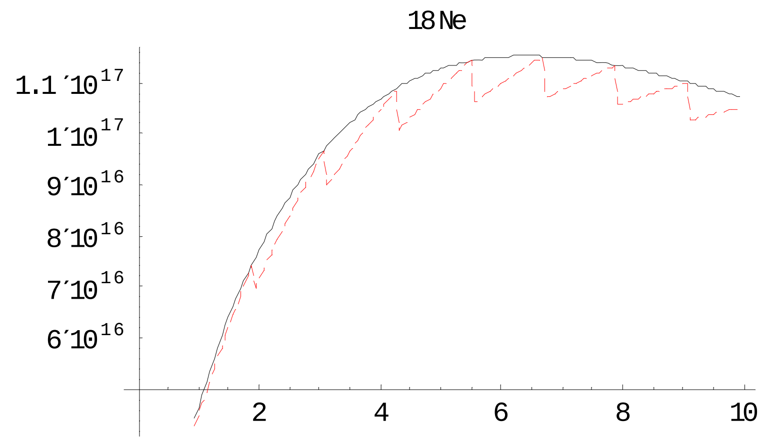
With an accumulation time in the PS of 4.3125 seconds,
a SPS repetitiontime of 6. seconds
and the standard dutycycle
the annual flux of 6He would be 3.44963×10^{18}
with 5.8138×10^{13} ions in the decay ring

Flux as a function of duty cycle

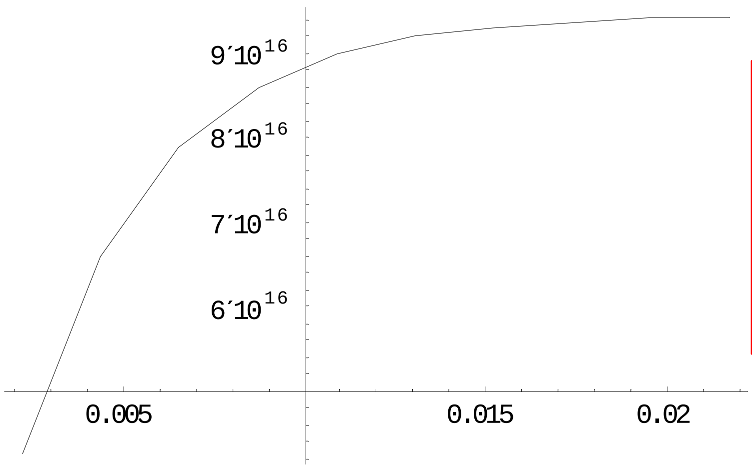
How to change the flux, ^{18}Ne



Flux as a function of gamma



Flux as a function of accumulation time in PS



Flux as a function of duty cycle

With an accumulation time in the PS of 5.5625 seconds,
, a SPS repetitiontime of 7.2 seconds
, 3 charge states in the linac
and the standard dutycycle
the annual flux of 18Ne would be 3.42769×10^{17},
with 5.8138×10^{13} ions in the decay ring

N.B. 3 charge states through the linac!

Baseline, version 2

- ECR source operates at 15 Hz
- PS receives 20 bunches
- No merging in PS and SPS
  - Tune shift respected
- With version 1 input for all other parameters for 10 years running (5+5):
  - Anti-neutrinos: $1.07\ 10^{19}$
  - Neutrinos: $2.65\ 10^{17}$

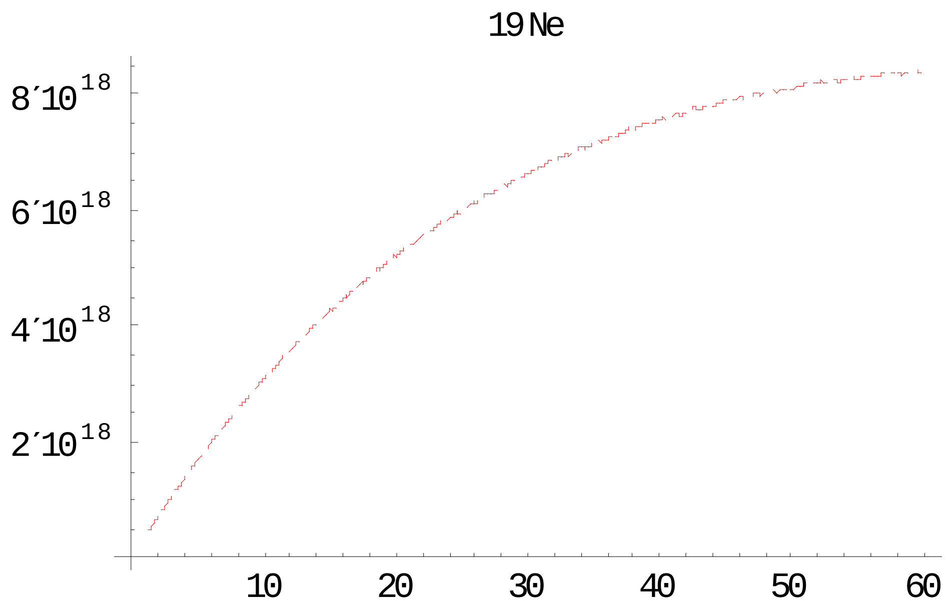
^{19}Ne?

- 19Ne:

$$^{19}_{10}Ne \rightarrow ^{19}_{9}F\ e^{+} \nu$$

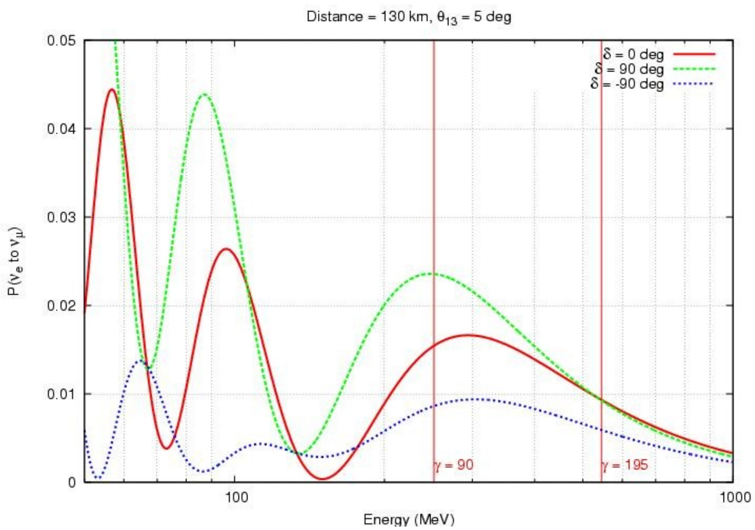
$$Q_{\beta} = 2.2\ \mathrm{MeV}$$

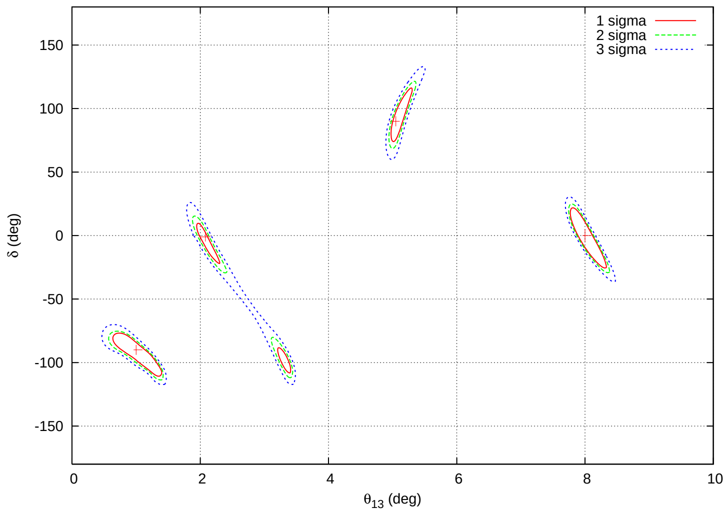
$$t_{1/2} = 17.22\ \mathrm{s}$$



- With three linacs and accumulation
  - New PS
  - Accumulation ring
  - Three linacs
  - SPS tune shift?

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
$^{148}Dy \to {}^{148}Tb^*$	3.1 m	1	0.96	0.96	0.46	620		2682	2062	
$^{150}Dy \to {}^{150}Tb^*$	7.2 m	0.64	1	1	0.32	397		1794	1397	
$^{152}Tm2^- \to {}^{152}E_T^*$	8.0 s	1	0.45	0.50	0.48	4300	520	8700	4400	520
$^{150}Ho2^- \to {}^{150}Dy^*$	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 ions/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**
- 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.