A BASELINE BETA-BEAM

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on behalf of the
Beta-beam Study Group

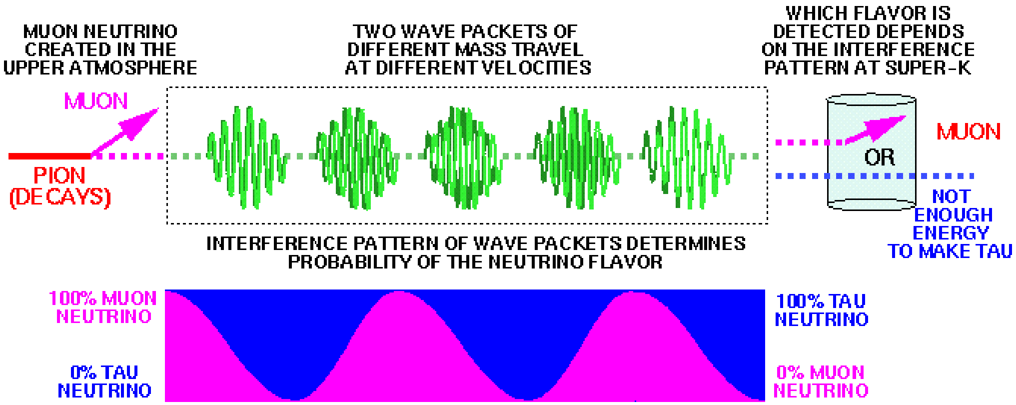
http://cern.ch/beta-beam/

Outline

- **Beta-beam baseline design**
  - A baseline scenario, ion choice, main parameters
  - Ion production
  - Decay ring design issues
- **Ongoing work and recent results**
  - Asymmetric bunch merging for stacking in the decay ring
  - Decay ring optics design & injection
- **Future R&D within EURISOL**
  - The Beta-beam Task
- **Conclusions**

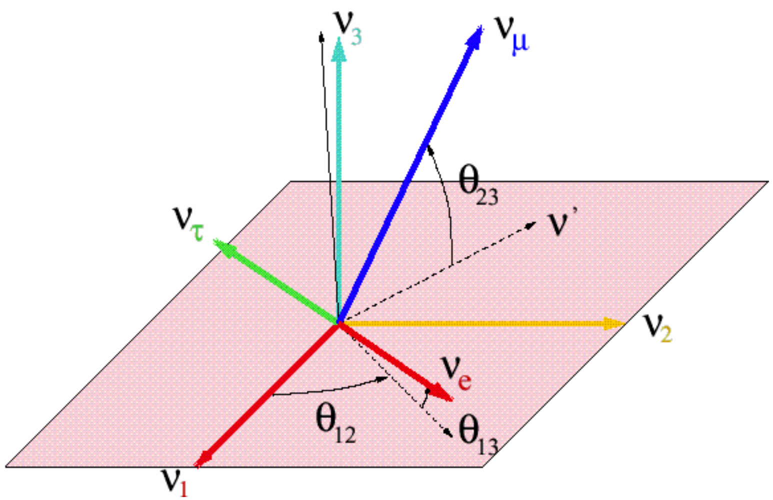
Neutrinos

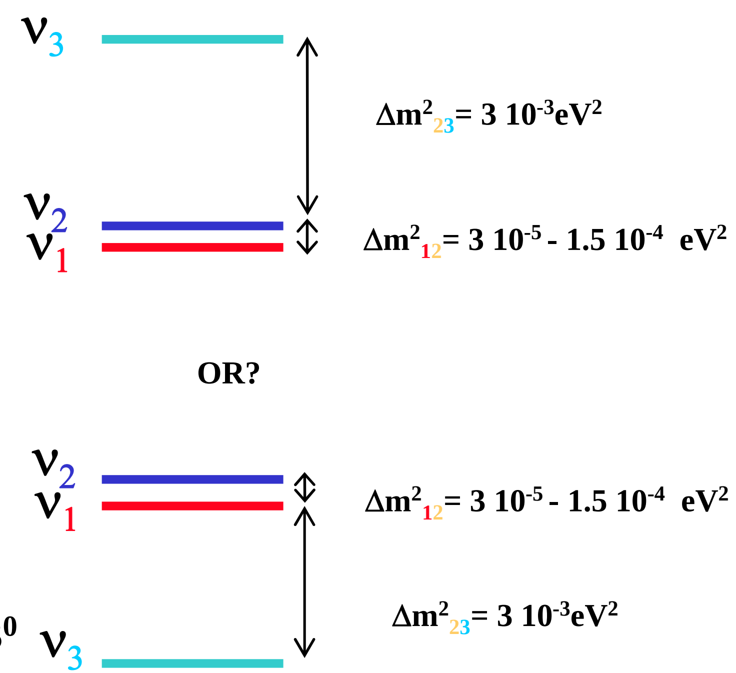
- A mass less particle predicted by Pauli to explain the shape of the beta spectrum
- Exists in at least three flavors (e, μ, τ)
- Could have a small mass which could significantly contribute to the mass of the universe
- The mass could be made up of a combination of mass states
  - If so, the neutrino could "oscillate" between different flavors as it travel along in space



Neutrino oscillations

- Three neutrino mass states (1,2,3) and three neutrino flavors (e,μ,τ)





θ_{23} (atmospheric) = 45^0, θ_{12} (solar) = 30^0, θ_{13} (Chooz) < 13^0

$$U_{MNS}: \begin{pmatrix} \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin\theta_{13}\, e^{i\delta} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2} \end{pmatrix}$$

Unknown or poorly known even after approved program:
θ_{13} , phase δ , sign of Δm_{13}

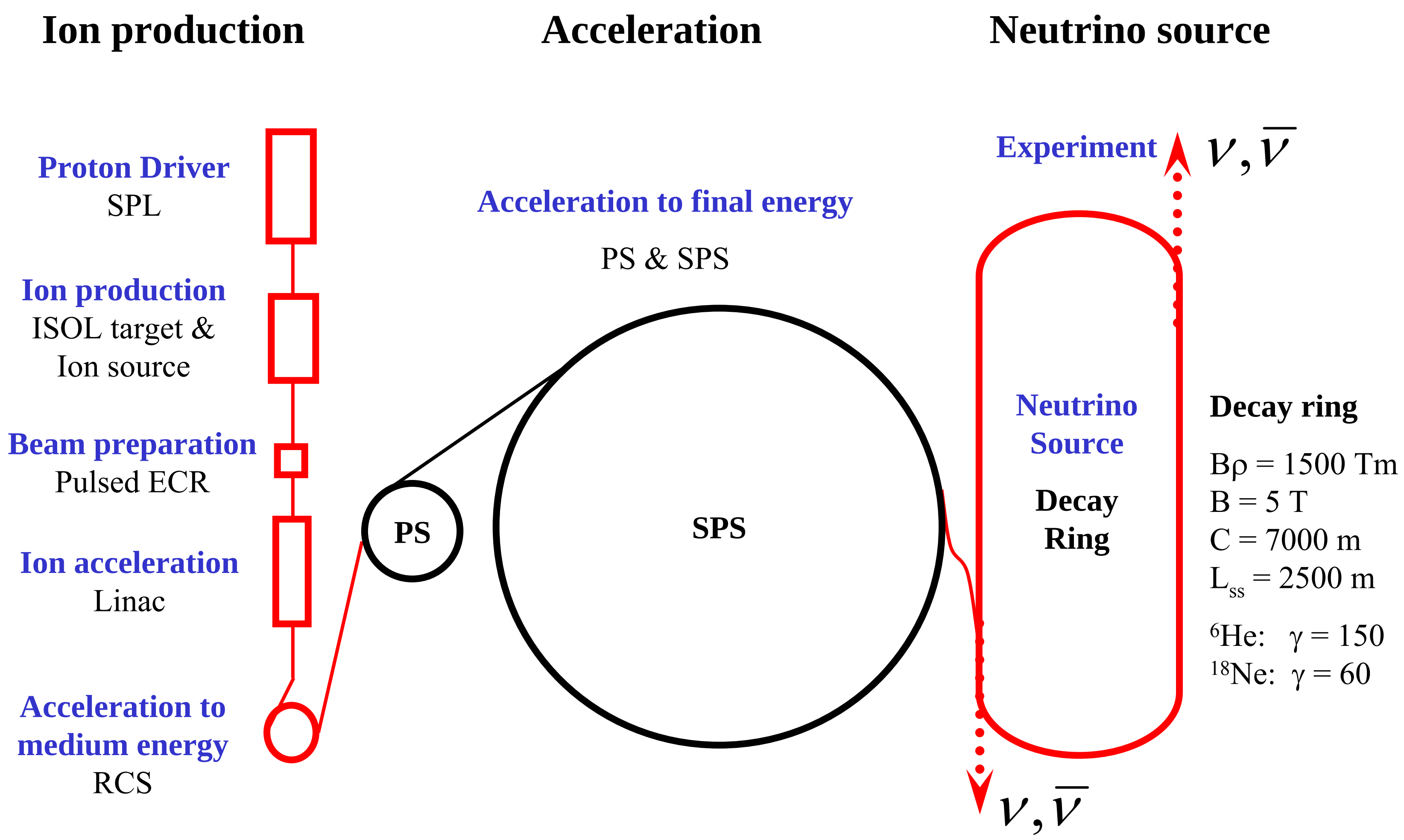
Introduction to beta-beams

- **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.**

- **Baseline scenario**
  - **Avoid anything that requires a "technology jump" which would cost time and money (and be risky).**
  - **Make maximum use of the existing infrastructure.**

Beta-beam baseline design



Main parameters (1)

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

    $\text{Average } E_{cms} = 1.937 \text{ MeV}$

  - **Neon-18 to produce neutrinos:** $^{18}_{10}Ne \rightarrow ^{18}_{9}F\ e^{+}\nu$

    $\text{Average } E_{cms} = 1.86 \text{ MeV}$

FLUX

- The Design Study is aiming for:
  - A beta-beam facility that will run for a "normalized" year of 10^7 seconds
  - An integrated flux of 10 10^{18} anti-neutrinos (^6He) and 5 10^{18} neutrinos (^{18}Ne) in ten years running 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

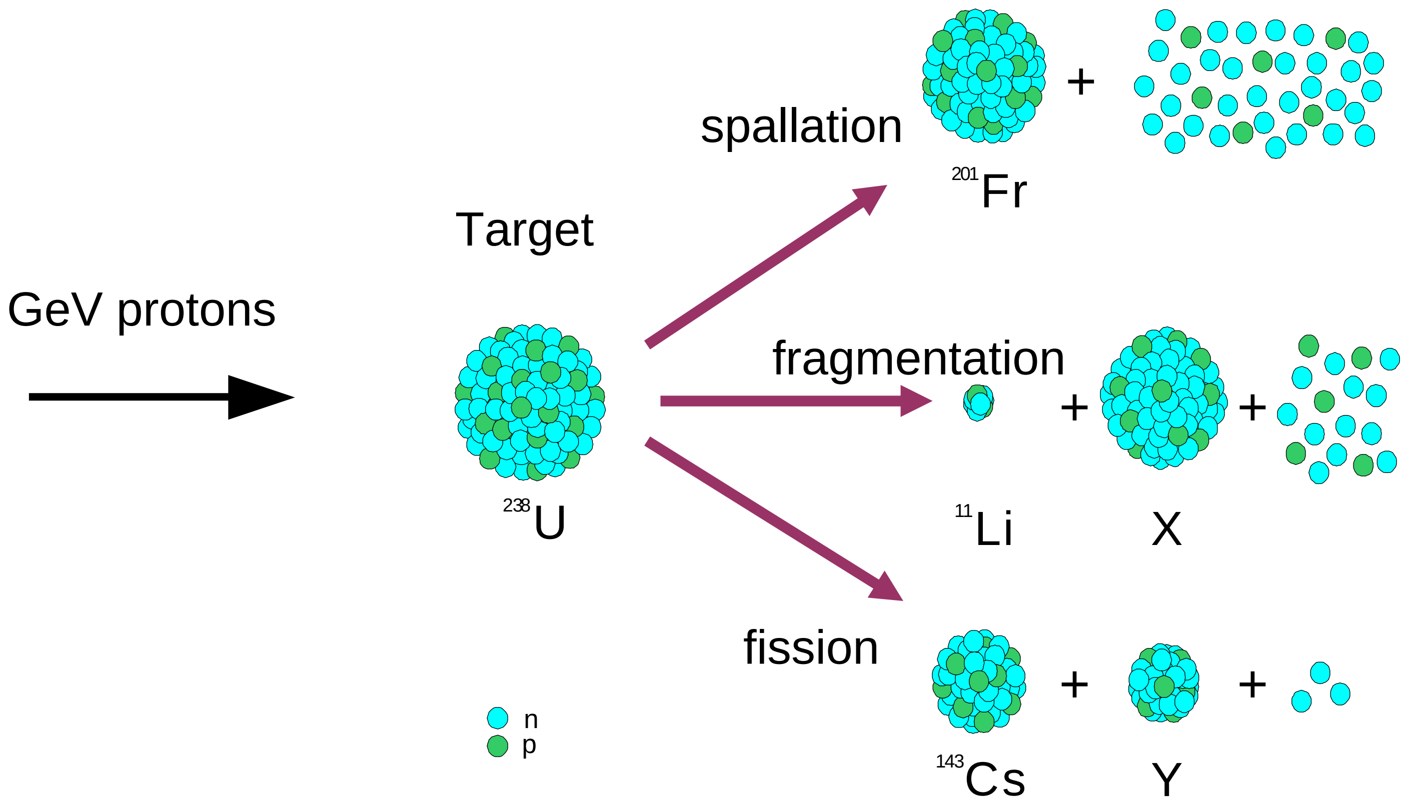
- The ultimate beta-beam facility flux would be for anti-neutrinos 29 10^{18} and for neutrinos 11 10^{18} in ten years running

Ion production - ISOL method

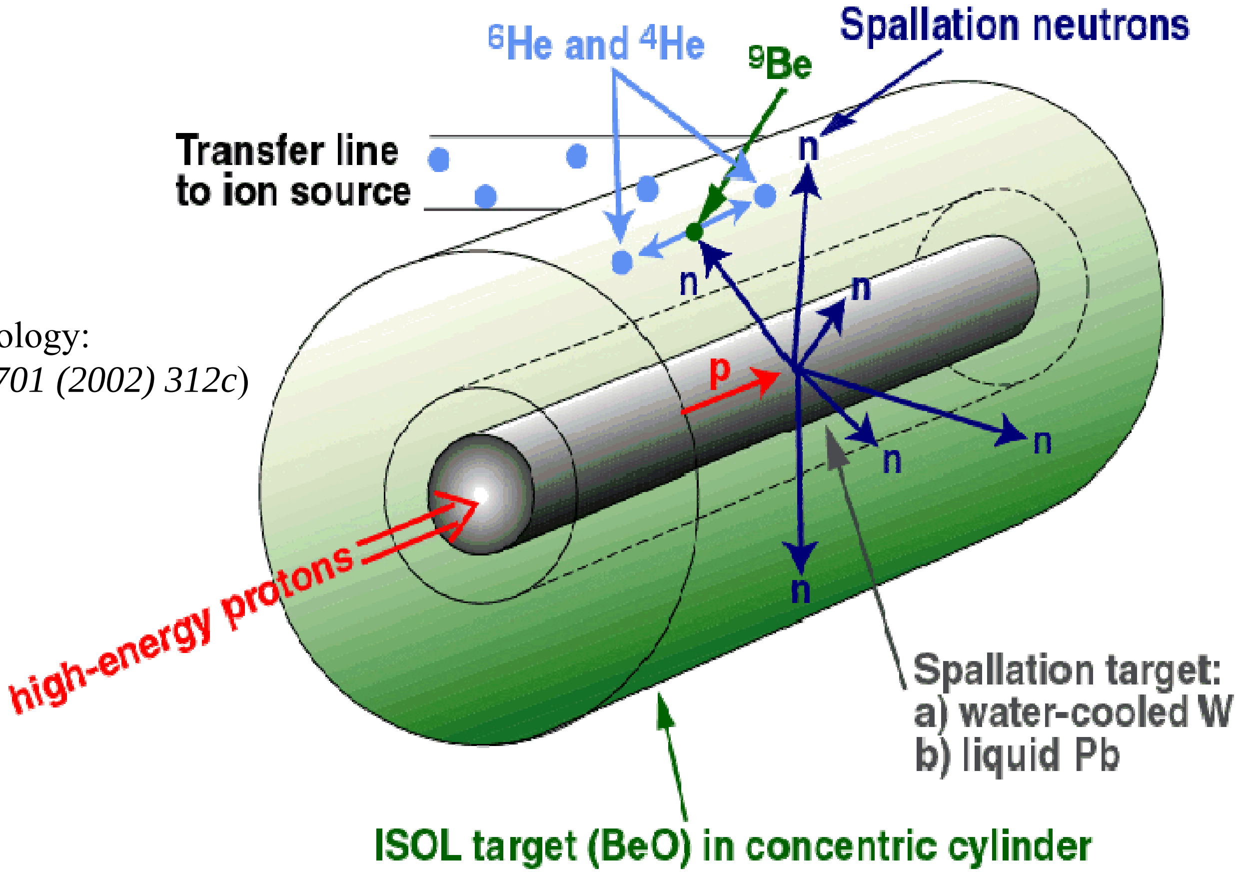
- **Isotope Separation OnLine method.**
- **Few GeV proton beam onto fixed target.**

^{6}He via spallation n

^{18}Ne directly



^{6}He production from ^{9}Be(n,α)



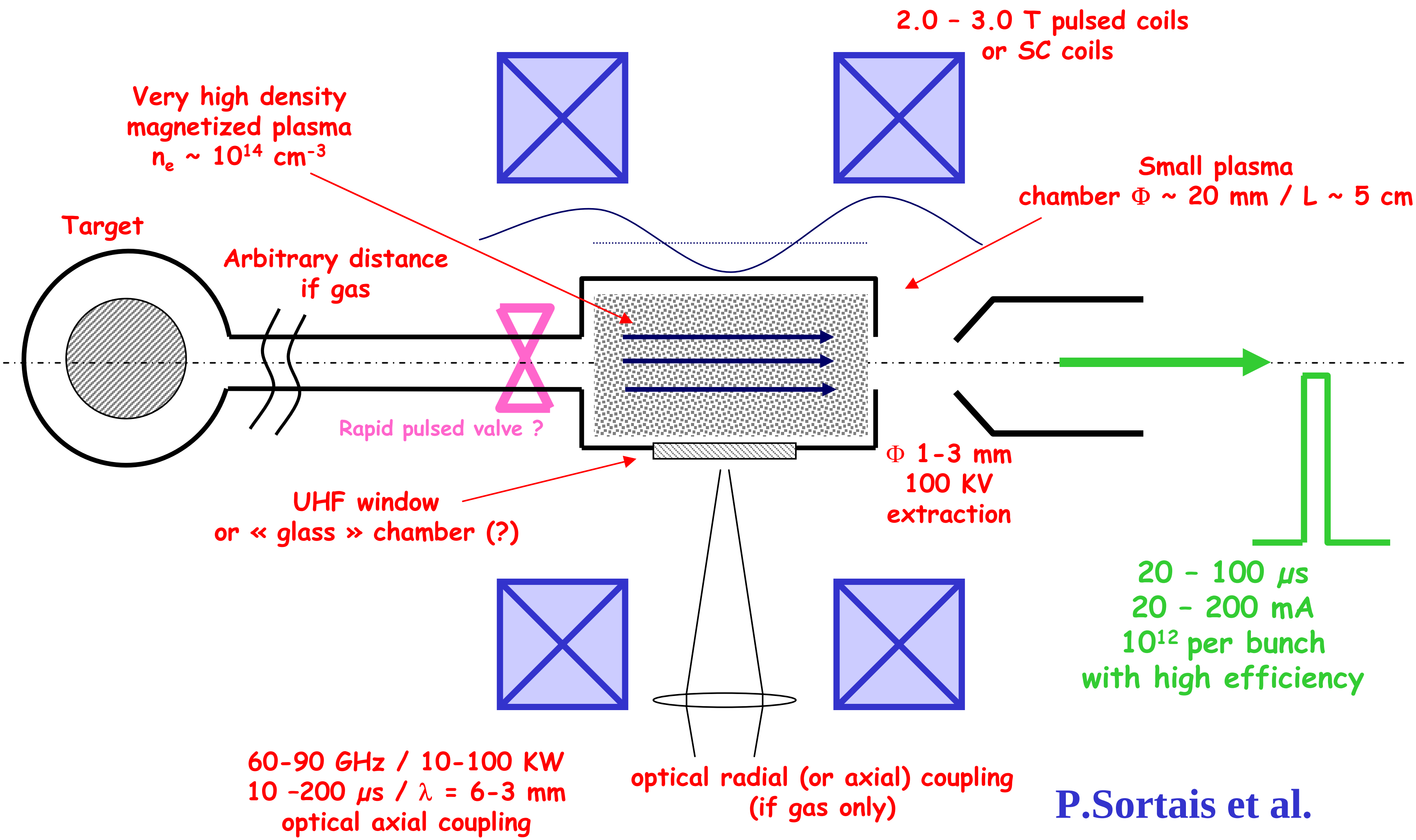
Converter technology:
(*J. Nolen, NPA 701 (2002) 312c*)

- **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

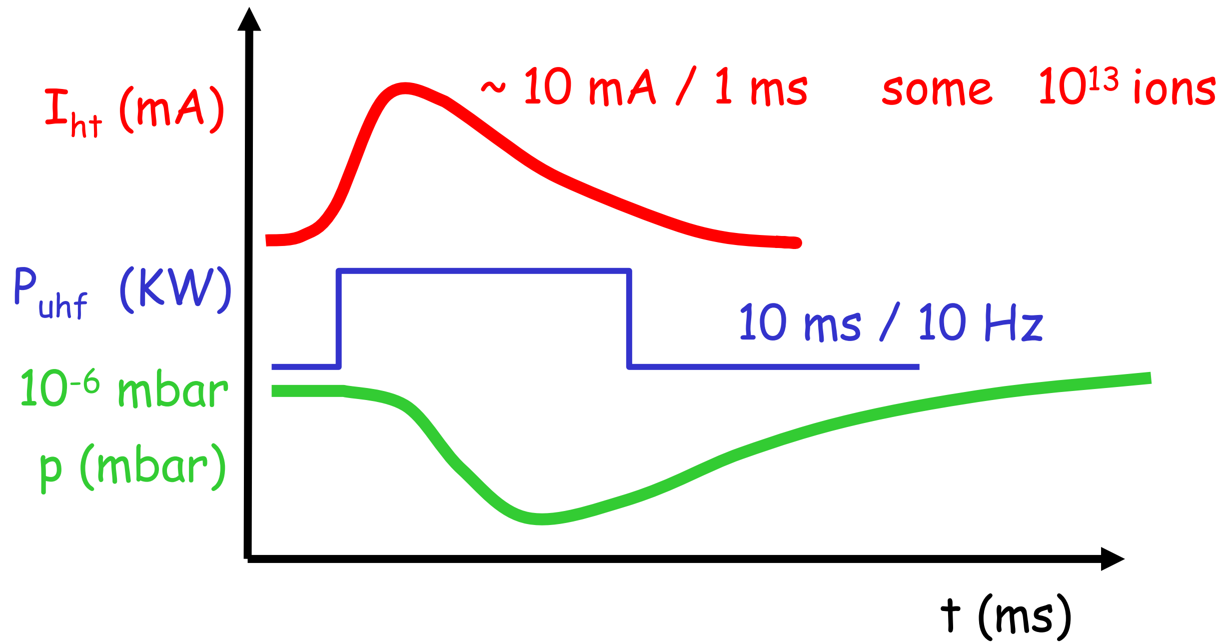
- **Spallation of close-by target nuclides**
  - $^{24}Mg^{12}$ (p, p_3 n_4) $^{18}Ne^{10}$.
  - Converter technology cannot be used; the beam hits directly the magnesium oxide target.
  - Production rate for ^{18}Ne is ~ $1x10^{12}$ ions/s (dc) for ~200 kW on target.
  - ^{19}Ne can be produced with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

60 GHz « ECR Duoplasmatron » for gaseous RIB



P.Sortais et al.

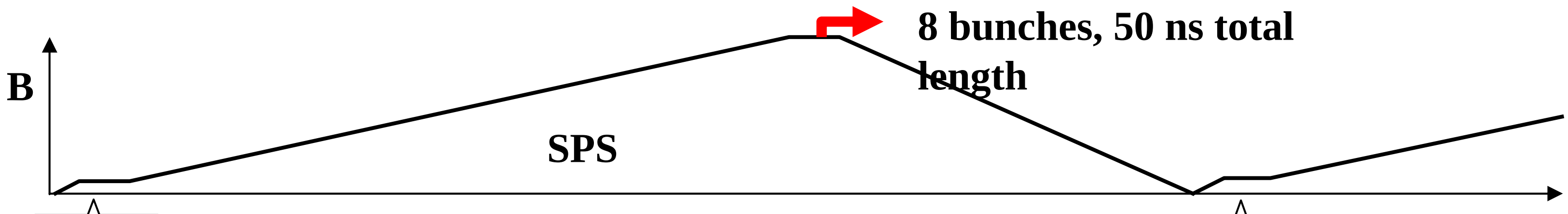
PHOENIX 28 GHz ionic pumping during preglow effect

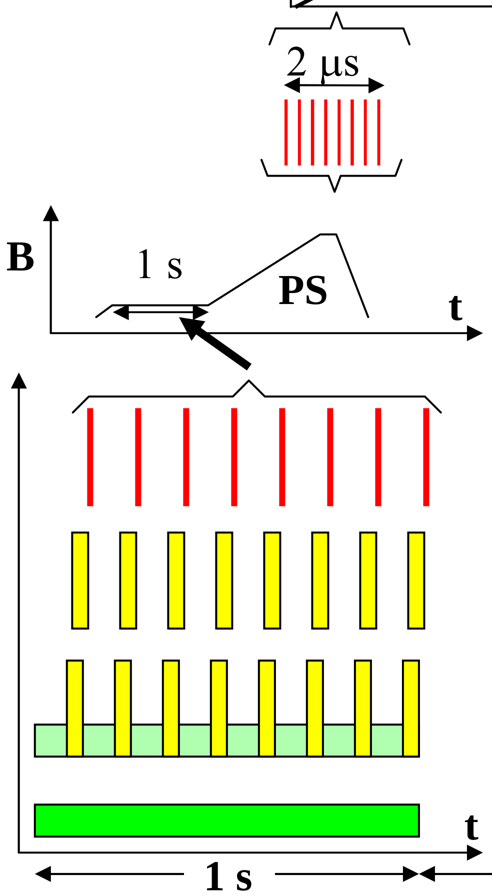


Some 10^{-6} mbar / 2 liters plasma chamber / some 10^{13} atoms

P.Sortais et al.

From dc to very short bunches





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

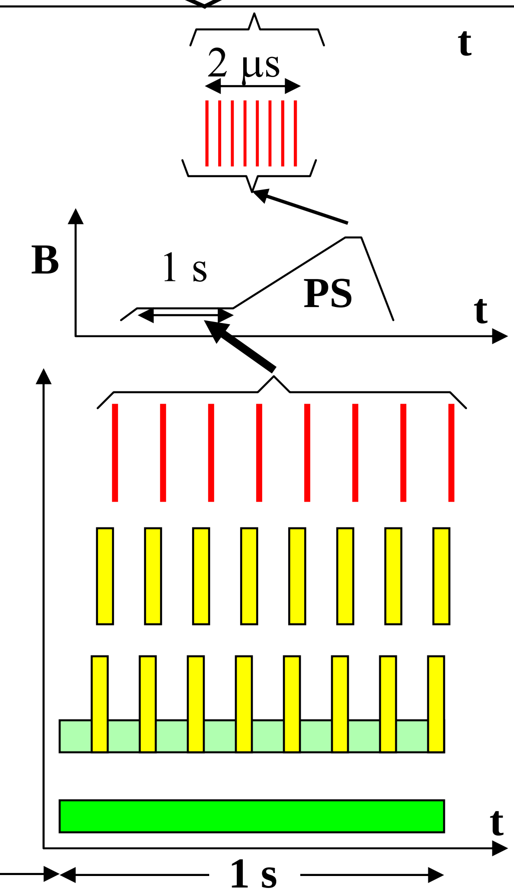
PS: 1 s flat bottom with 16 injections. Acceleration in ~1 s to ~86.7 Tm..

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

Intensities, 6He

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

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.

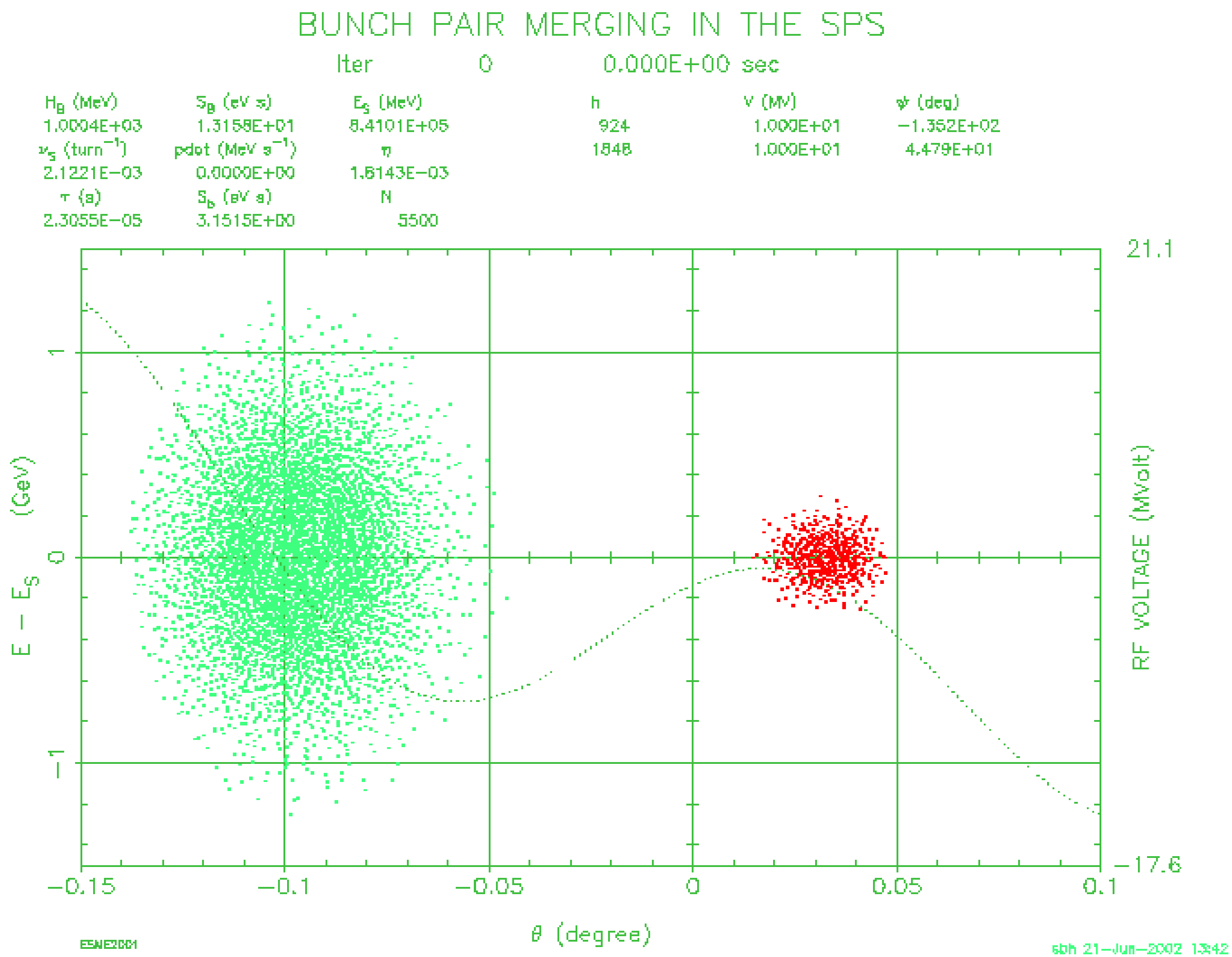
Decay ring design aspects

- 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

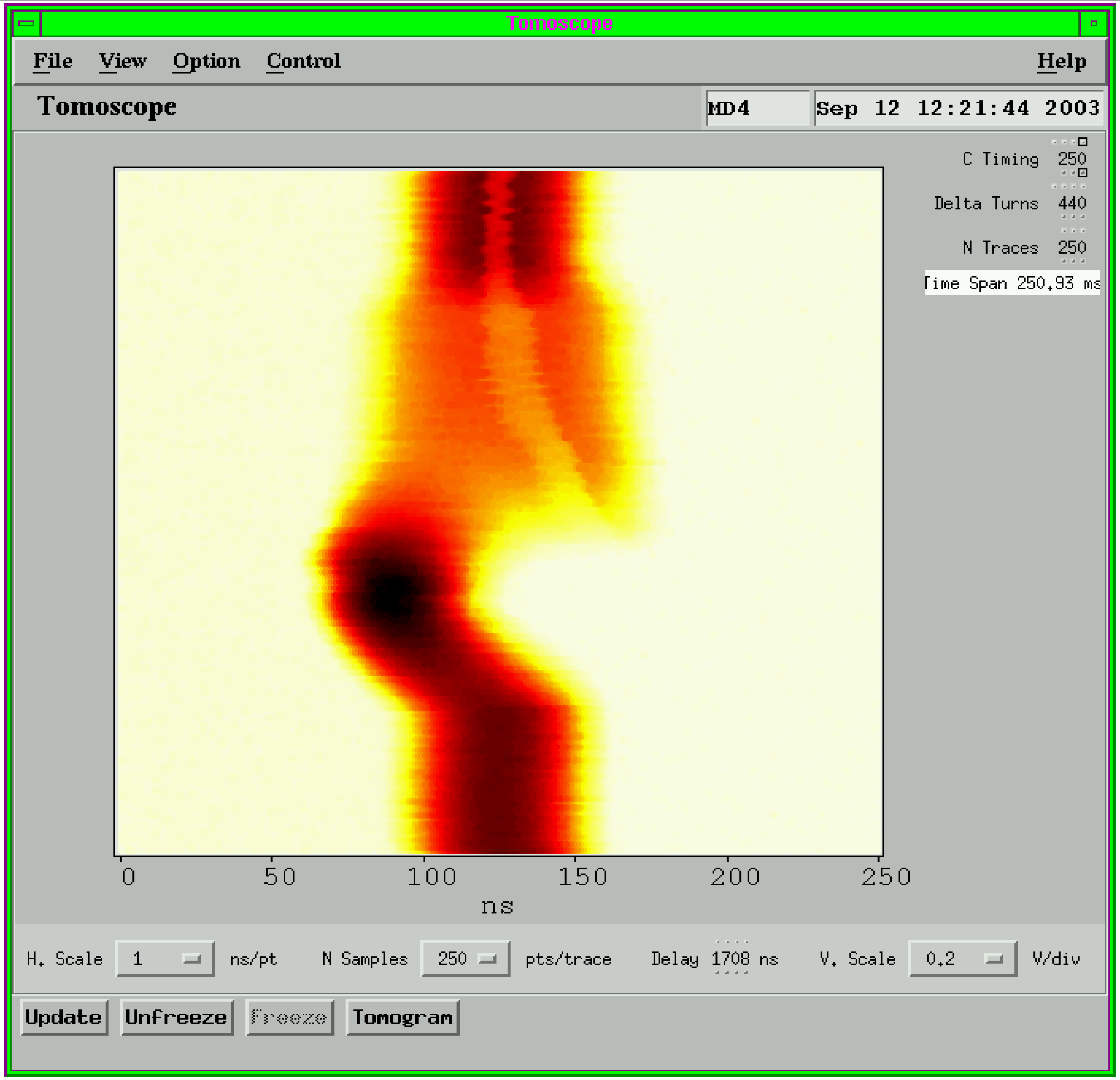
Asymmetric bunch pair merging

- 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 the PS

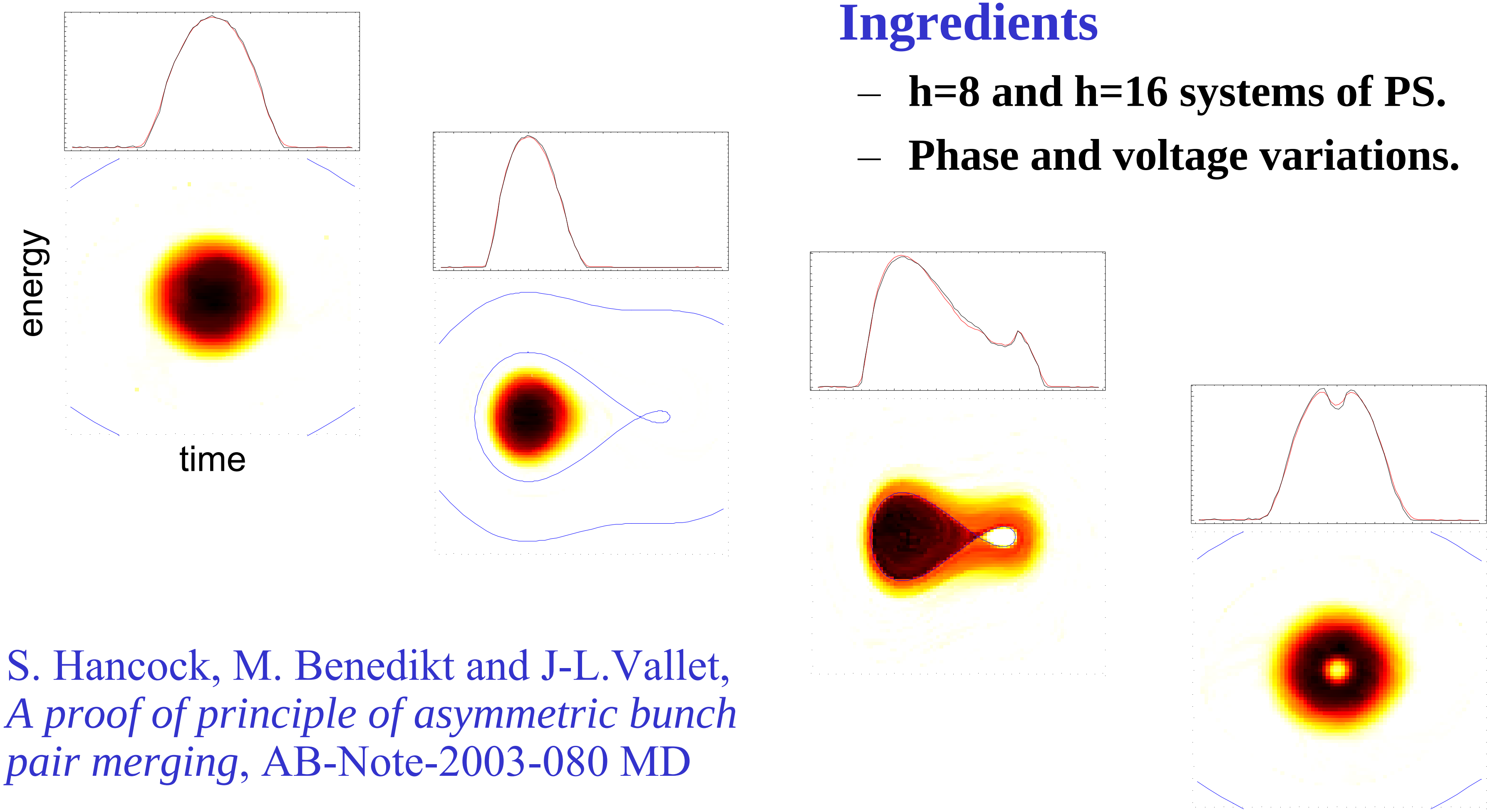


A large bunch is merged with a small amount of empty phase space.

Longitudinal emittances are combined.

Minimal blow-up.

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

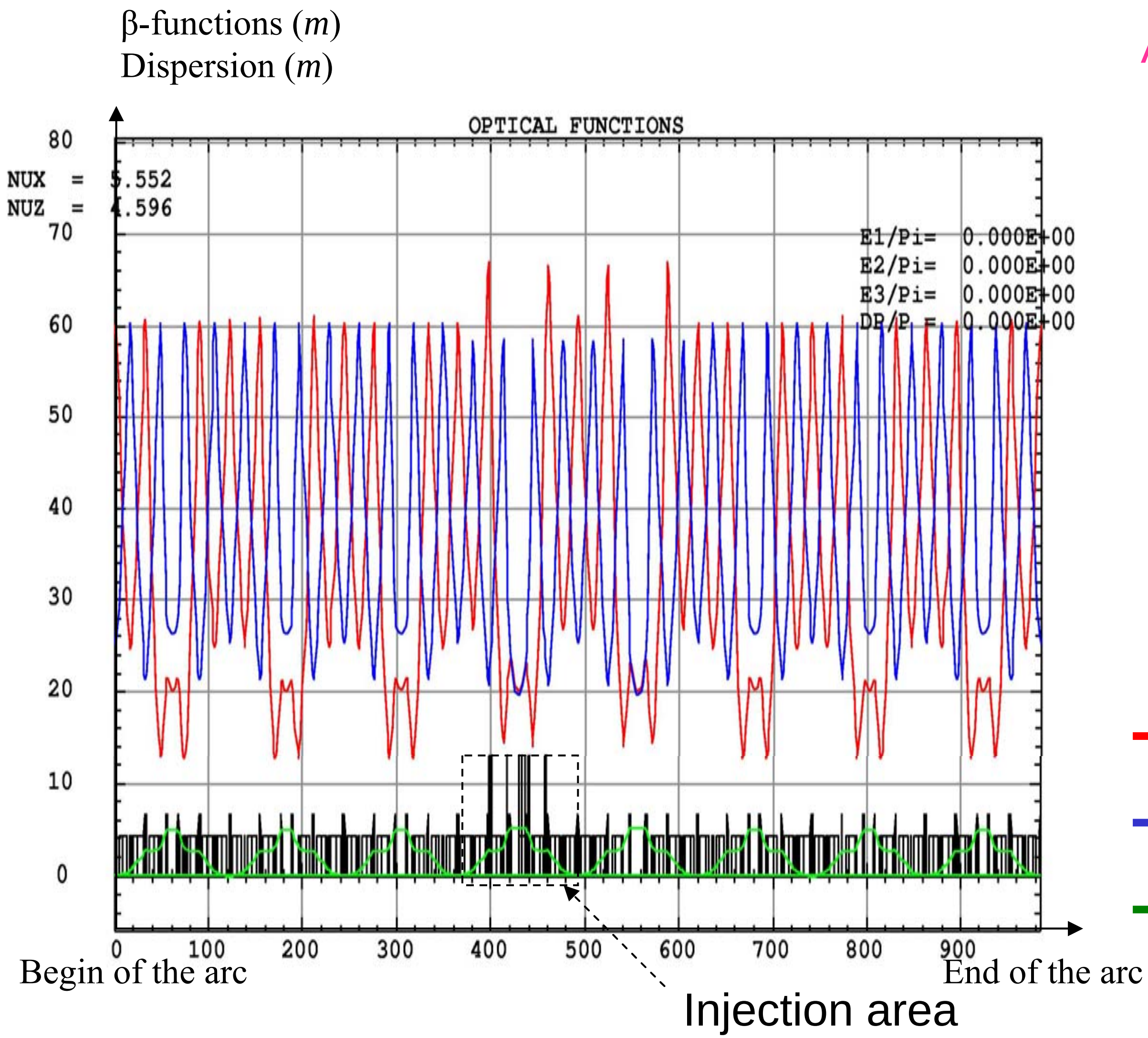
Decay ring injection design aspects

- **Asymmetric merging requires fresh bunch injected very close longitudinally to existing stack. Conventional injection with fast elements (septa and kickers) is excluded.**

- **Alternative injection scheme**
  - **Inject an off-momentum beam on matched dispersion trajectory.**
  - **No fast elements required (bumper rise and fall ~10 μs).**
  - **Requires large normalized dispersion at injection point (small beam size and large separation due to momentum difference).**
  - **Price to be paid is larger magnet apertures in decay ring.**

Decay ring arc lattice design

A. Chance, CEA-Saclay (F)



FODO structure

Central cells detuned for injection

Arc length ~984m

Bending 3.9 T, ~480 m L_{eff}

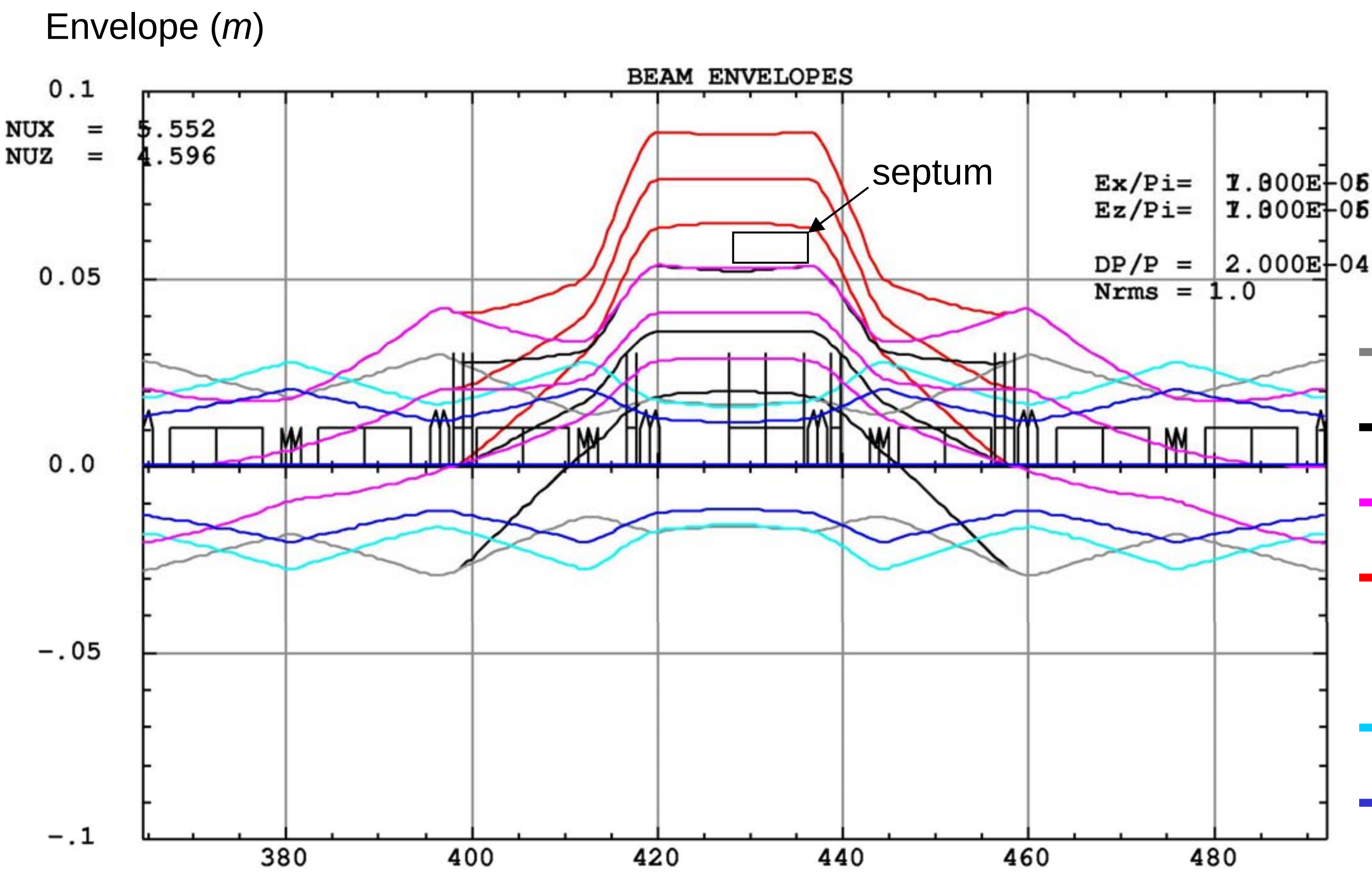
5 quadrupole families

— Horizontal β_x

— Vertical β_y

— Horizontal Dispersion D_x

A. Chance, CEA-Saclay (F)



Horizontal envelopes :

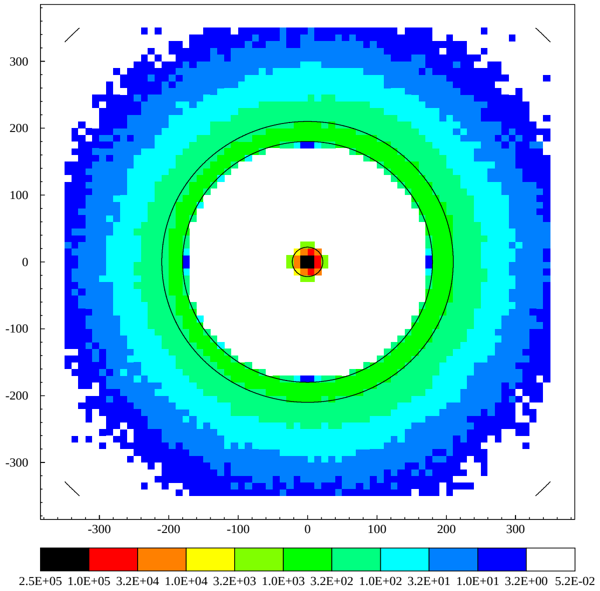
- Δp/p = 0 bumps off
- Δp/p = 0 bumps on
- Δp/p = 0.8% bumps off
- Δp/p = 0.8% bumps on

Vertical envelopes :

- stored beam
- injected beam

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)

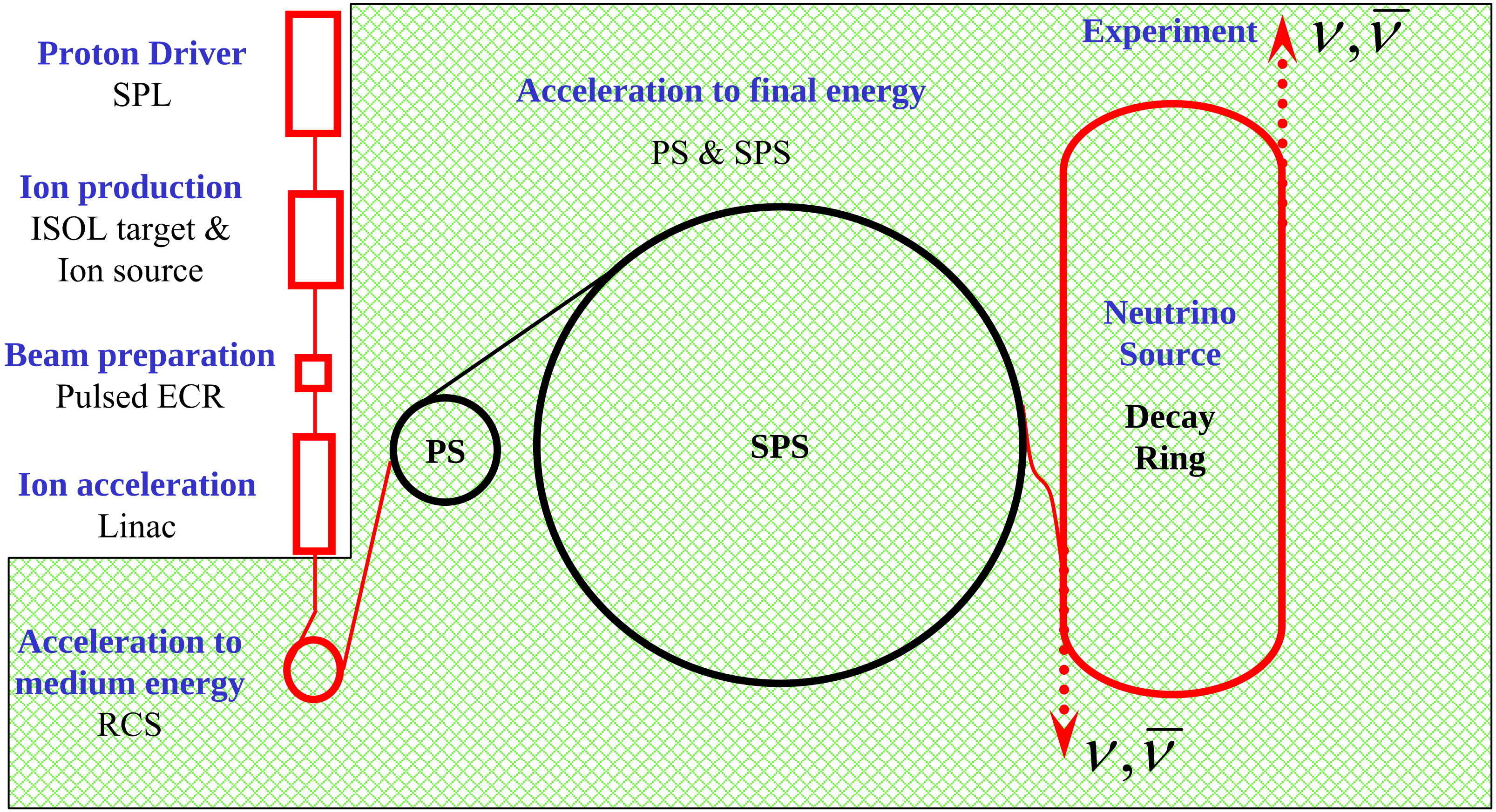
Future R&D

- **Future beta-beam R&D together with EURISOL project**
- **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.**

Beta-beam task

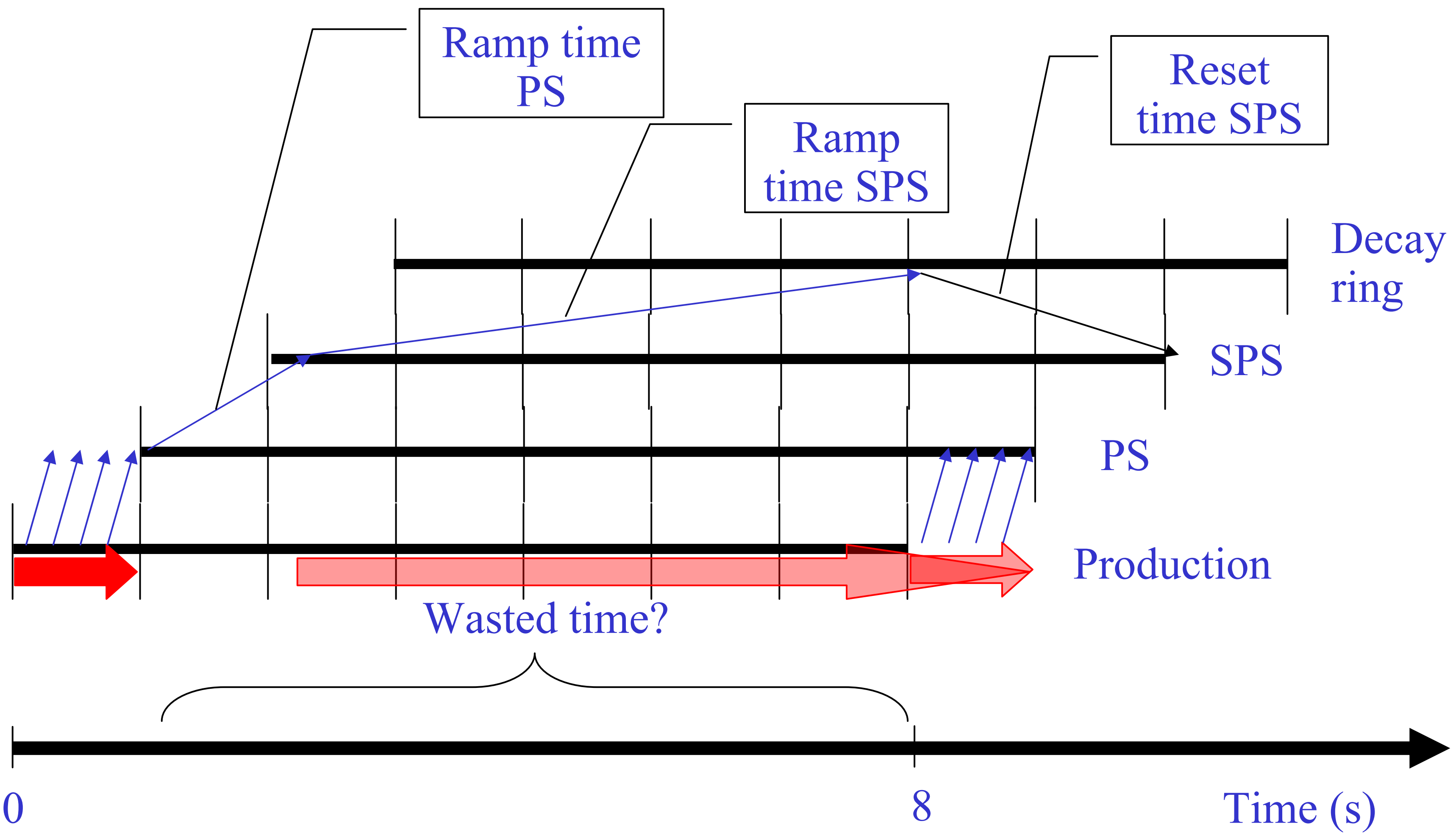
From exit of the heavy ion Linac (~100 MeV/u) to the decay ring (~100 GeV/u).



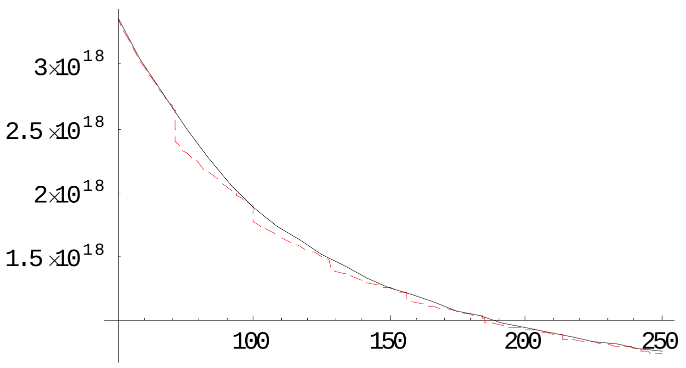
Beta-beam sub-tasks

- Beta-beam task starts at exit of EURISOL post accelerator and comprises the conceptual design of the complete chain up to the decay ring.
- Participating insitutes: CERN, CEA-Saclay, IN2P3, CLRC-RAL, GSI, MSL-Stockholm.
- Organized by a steering committee overseeing 3 sub-tasks.
  - 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.
  - Detailed work and manpower planning is under way.
  - 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).

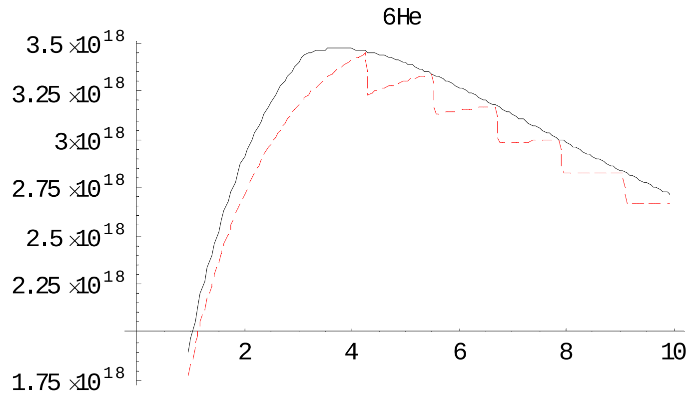
Wasted time or accumulation time?



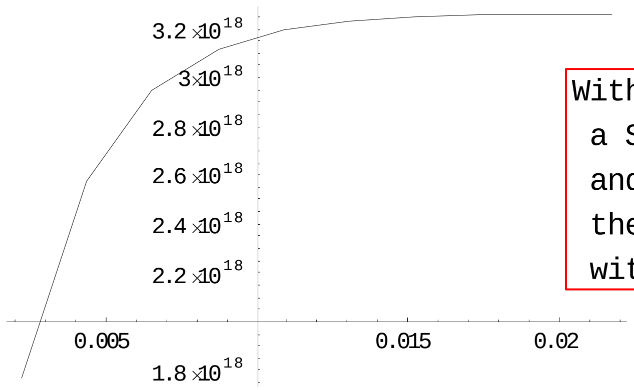
How to change the flux, ^{6}He



Flux as a function of gamma



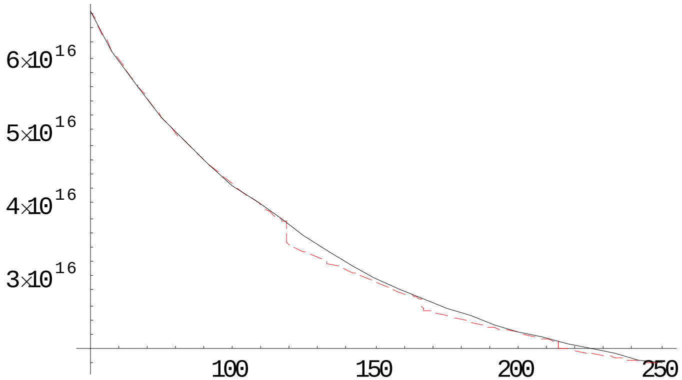
Flux as a function of accumulation time in PS



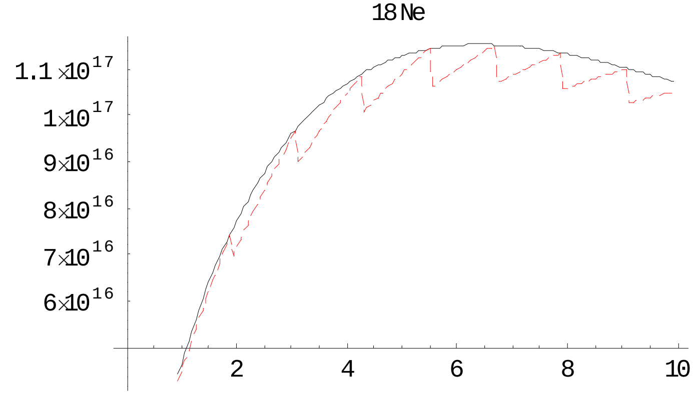
Flux as a function of duty cycle

With an accumulation time in the PS of 4.3125 seconds,
a SPS repetitiontime of 6. seconds
and the standard dutycycle
the annual flux of 6He would be 3.44819×10^{18}
with 5.81137×10^{13} ions in the decay ring

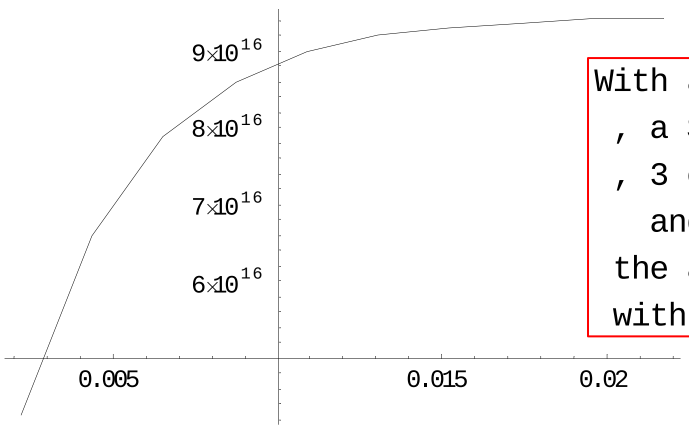
How to change the flux, ^{18}Ne



Flux as a function of gamma



Flux as a function of accumulation time in PS

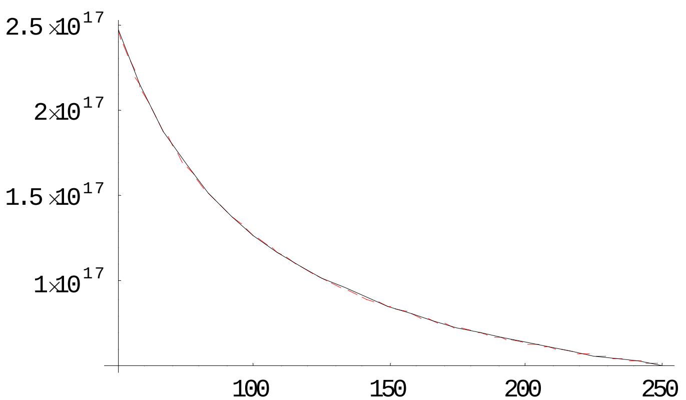


Flux as a function of duty cycle

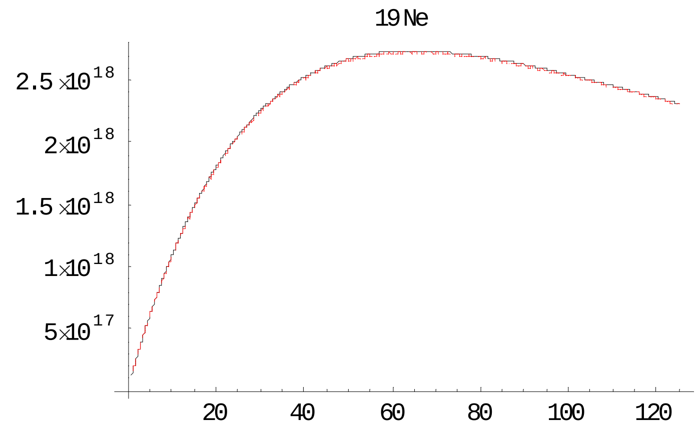
```
With an accumulation time in the PS of 5.5625 seconds,
 , a SPS repetitiontime of 7.2 seconds
 , 3 charge states in the linac
   and the standard dutycycle
 the annual flux of 18Ne would be 3.427×10^17 ,
 with 2.77284×10^12 ions in the decay ring
```

N.B. 3 charge states through the linac!

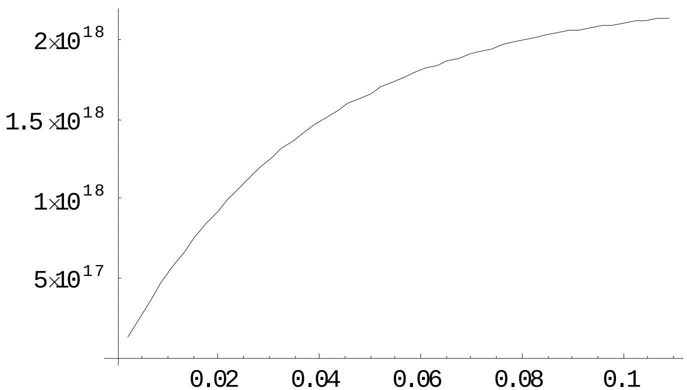
How to change the flux, ^{19}Ne



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 56.25 seconds,
 , a SPS repetitiontime of 58.8 seconds
 , 3 charge states in the linac
   and the standard dutycycle
 the annual flux of 19Ne would be 7.94514×10^18
 with 8.55587×10^13 ions in the decay ring
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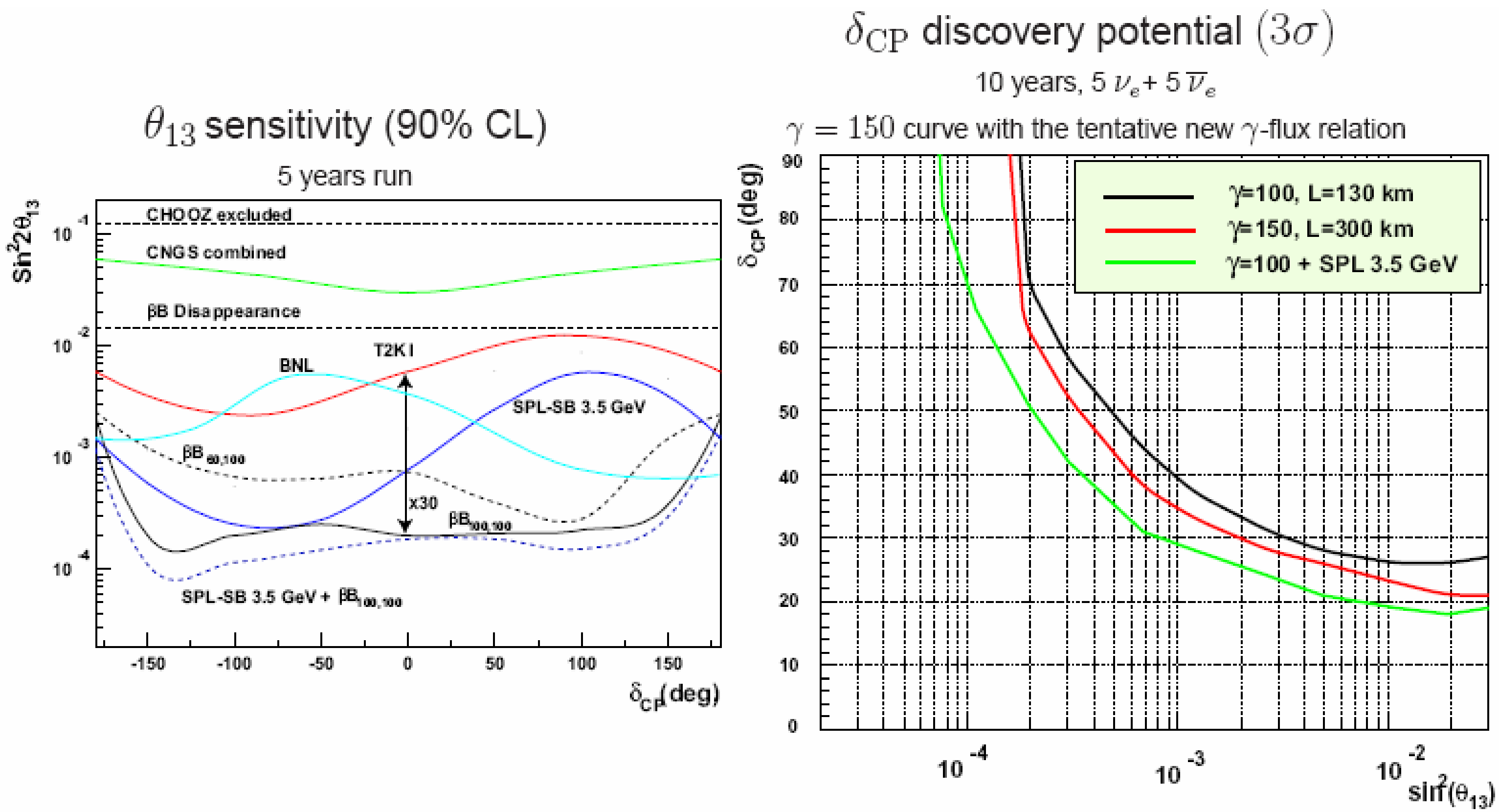
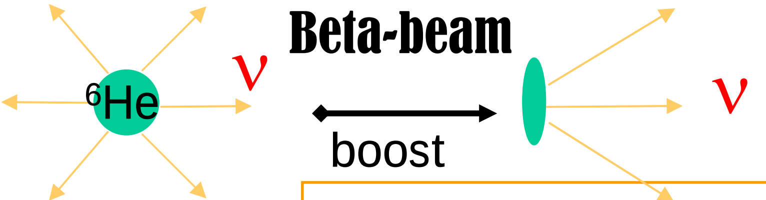
N.B. 3 charge states through the linac!

Physics reach
Ultimate beta-beam, gamma=100/100



M. Mezzetto, " Physics with BetaBeams and SuperBeams from CERN to Frejus", NNN05, Aussois, 08 April 2005. 22

LOW-ENERGY BETA-BEAMS



C. Volpe, hep-ph/0303222
Journ. Phys. G. 30(2004)L1

THE PROPOSAL

To exploit the beta-beam concept to produce intense and pure low-energy neutrino beams.

PHYSICS POTENTIAL

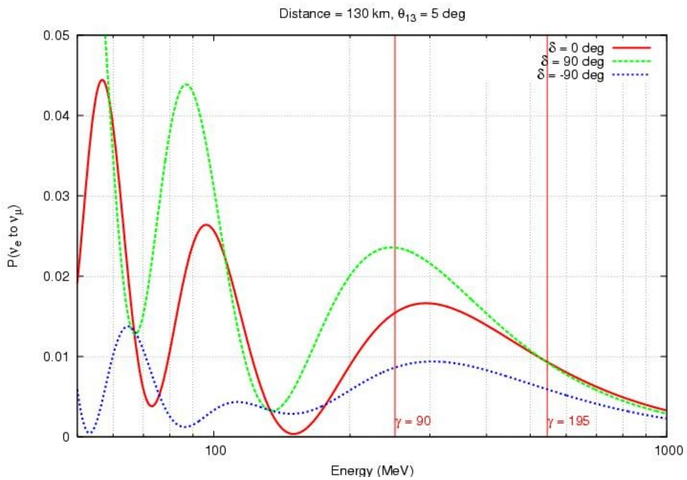
- Neutrino-nucleus interaction studies for particle, nuclear physics, astrophysics (nucleosynthesis).

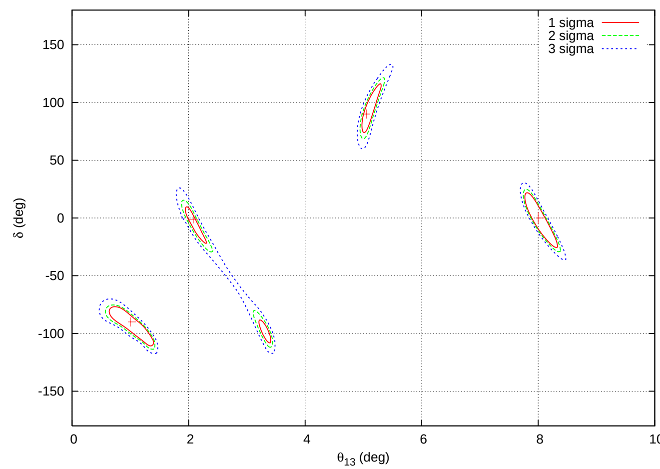
  Important for neutrinoless double-beta decay.

  C. Volpe, hep-ph/0501233

- Neutrino properties, like ν magnetic moment.

EC or the dream of monochromatic neutrino beams





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

Conclusions

- **Well-established beta-beam baseline scenario.**
- **Beta-Beam Task well integrated in the EURISOL DS.**
  - **Strong synergies between Beta-beam and EURISOL.**
- **Design study started for "base line" isotopes.**
- **Baseline study should result in a credible conceptual design report.**
  - **We need a "STUDY 1" for the beta-beam to be considered a credible alternative to super beams and neutrino factories**
  - **New ideas welcome but the design study cannot (and will not) deviate from the given flux target values and the chosen baseline**
  - **Parameter list to be frozen by end of 2005**
- Recent new ideas promise a fascinating continuation into further developments beyond (but based on) the ongoing EURISOL (beta-beam) DS
  - Low energy beta-beam, EC beta-beam, High gamma beta-beam, etc.
- And this is only the beginning…