Beta-beams:
A neutrino factory based on radioactive ions

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CERN

on behalf of the Beta-beam Study Group

http://cern.ch/beta-beam

Acknowledgements

- EURISOL
- CERN:
  - Michael Benedikt, Adrian Fabich, Steven Hancock,
  - Mats Lindroos (providing course material)
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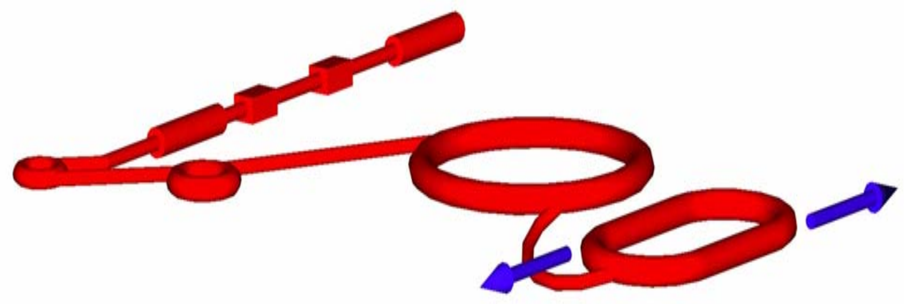
- Yacine Kadi, Vasilis Vlachoudis, Alfredo Ferrari
- Mauro Mezzetto, Piero Zuchelli
- Andreas Jansson at FNAL
- ANL collegues

…and many others

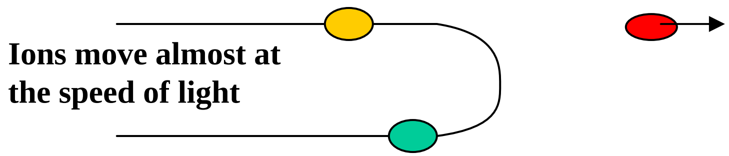
Outline

- Beta-beam concept
- EURISOL DS scenario
  - Layout
  - Progress of work
  - Challenges
- Beyond the EURISOL baseline
  - High gamma Beta-beams
  - Electron capture Beta-beams
  - High-Q vlaue Beta-beams
  - FNAL Beta-beam
- European Design Study proposal for a European Neutrino Oscillation Facility
- Summary



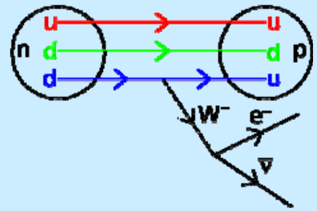
- **Beta-beam proposal by Piero Zucchelli**
  - ***A novel concept for a neutrino factory: the beta-beam,* Phys. Let. B, 532 (2002) 166-172.**

- **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.**

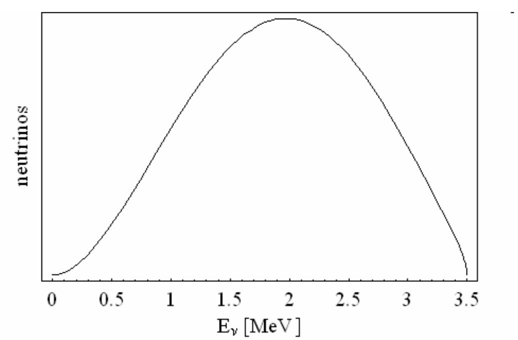
Beta-beam Basics



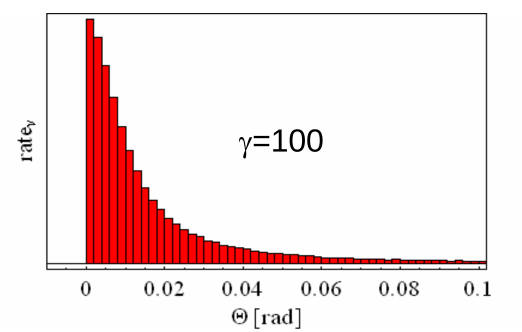
Aim: production of (anti-)neutrino beams from the beta decay of radio-active ions circulating in a storage ring

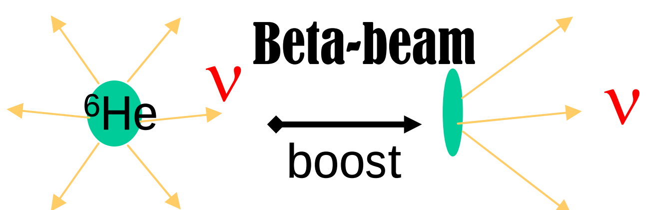
- Similar concept to the neutrino factory, but parent particle is a beta-active isotope instead of a muon.

- Beta-decay at rest
  - ν–spectrum well known from electron spectrum
  - Reaction energy Q typically of a few MeV
  - Only electron (anti-)neutrinos



- Accelerated parent ion to relativistic γ_{max}
  - Boosted neutrino energy spectrum: $E_\nu \leq 2\gamma Q$
  - Forward focusing of neutrinos: $\theta \leq 1/\gamma$





The EURISOL scenario

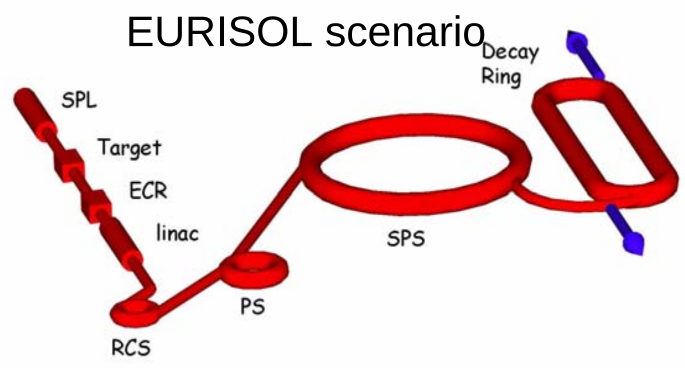
- Based on CERN boundaries
- Ion choice: ^{6}He and ^{18}Ne

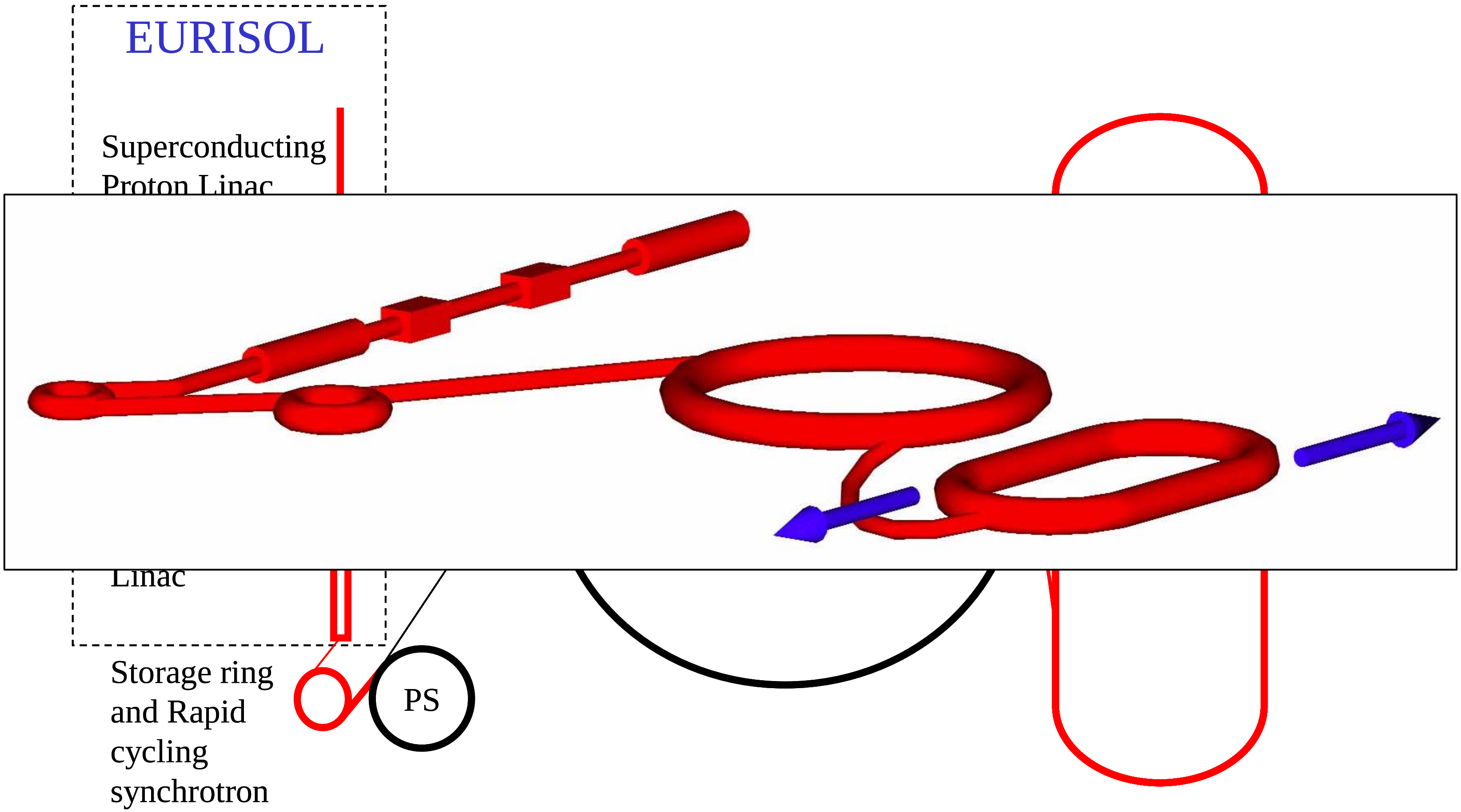
- Relativistic gamma=100/100
  - SPS allows maximum of 150 (^{6}He) or 250 (^{18}Ne)
  - Gamma choice optimized for physics reach

- Based on existing technology and machines
  - Ion production through ISOL technique
  - Bunching and first acceleration: ECR, linac
  - Rapid cycling synchrotron
  - Use of existing machines: PS and SPS

- Achieve an annual neutrino rate of either
  - 2.9×10^{18} anti-neutrinos from ^{6}He
  - Or $1.1\ 10^{18}$ neutrinos from ^{18}Ne

- Once we have thoroughly studied the EURISOL scenario, we can "easily" extrapolate to other cases. EURISOL study could serve as a reference.




EURISOL
Superconducting
Proton Linac
Linac
Storage ring
and Rapid
cycling
synchrotron
PS

Guideline to ν-beam scenarios

based on radio-active ions

- Low-energy beta-beam: relativistic $\gamma < 20$
  - Physics case: neutrino scattering
- Medium energy beta-beam: $\gamma \sim 100$
  - EURISOL DS
  - Today the only detailed study of a beta-beam accelerator complex
- High energy beta-beam: $\gamma > 350$
  - Take advantage of increased interaction cross-section of neutrinos
- Monochromatic neutrino-beam
  - Take advantage of electron-capture process
- High-Q value beta-beam: $\gamma \sim 100$

Accelerator physicists together with neutrino physicists defined the accelerator case of γ=100/100 to be studied first (EURISOL DS).

Which Radioactive ion is best?

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

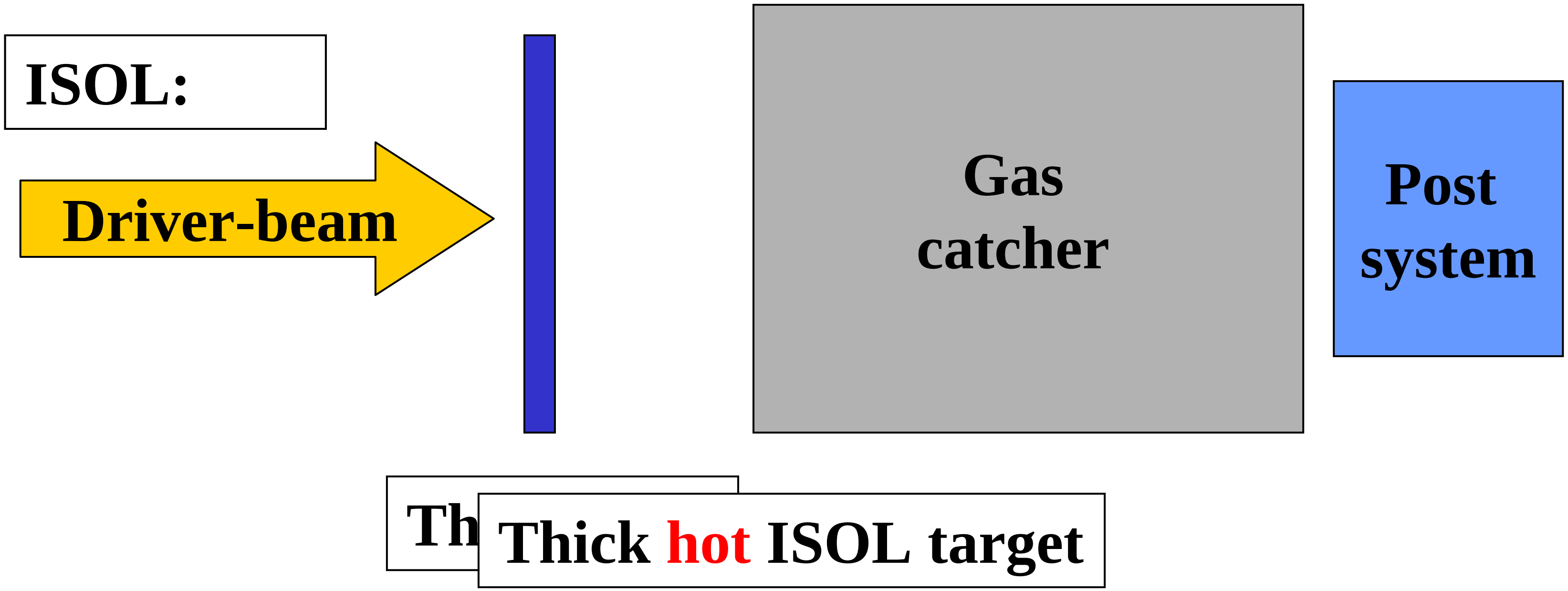
    Average $E_{cms} = 1.937$ MeV
  - **Neon-18 to produce neutrinos:** ${}^{18}_{10}Ne \rightarrow {}^{18}_{9}F\ e^{+}\nu$

    Average $E_{cms} = 1.86$ MeV

In-flight and ISOL

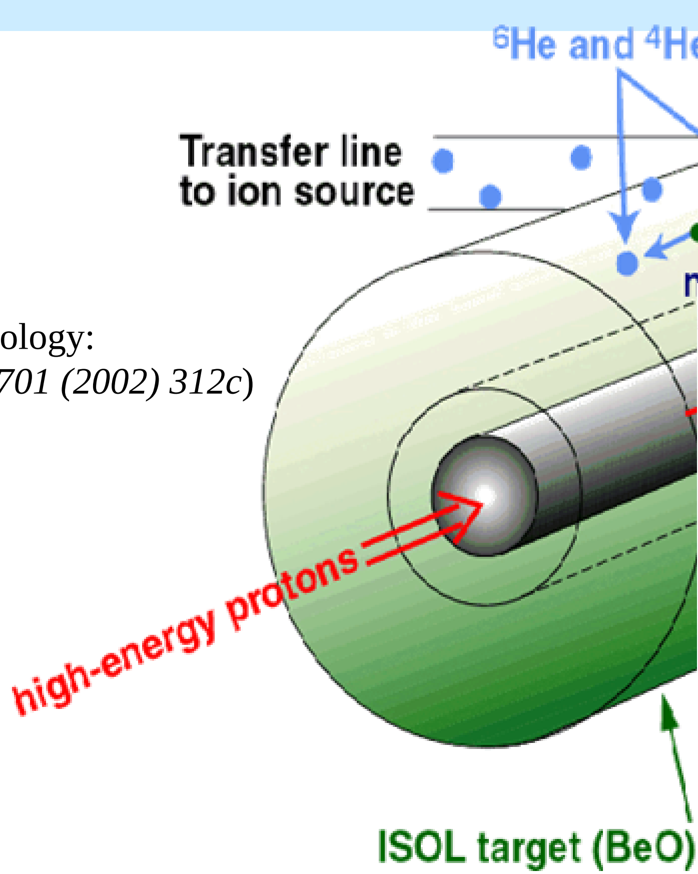
"ISOL: Such an instrument is essentially a target, ion source and an electromagnetic mass analyzer coupled in series. The apparatus is said to be on-line when the material analyzed is directly the target of a nuclear bombardment, where reaction products of interest formed during the irradiation are slowed down and stopped in the system.

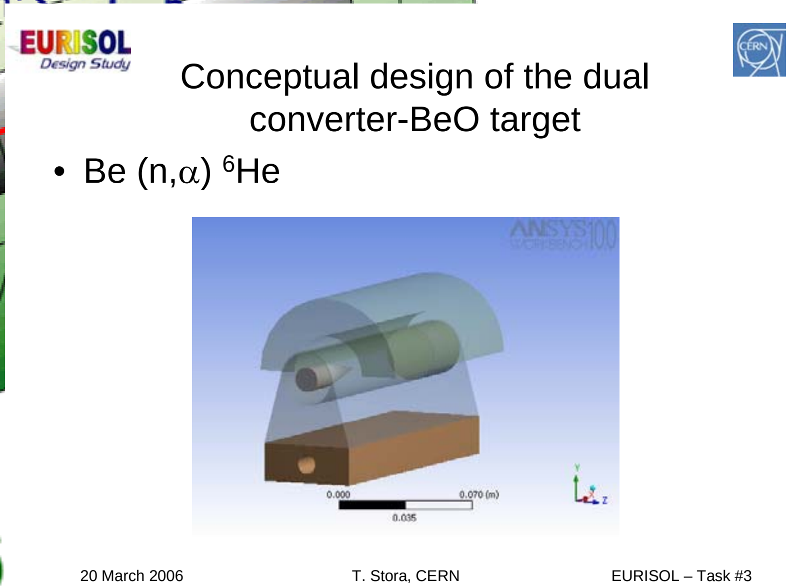
H. Ravn and B.Allardyce, 1989, Treatise on heavy ion science



^{6}He production from ^{9}Be(n,α)

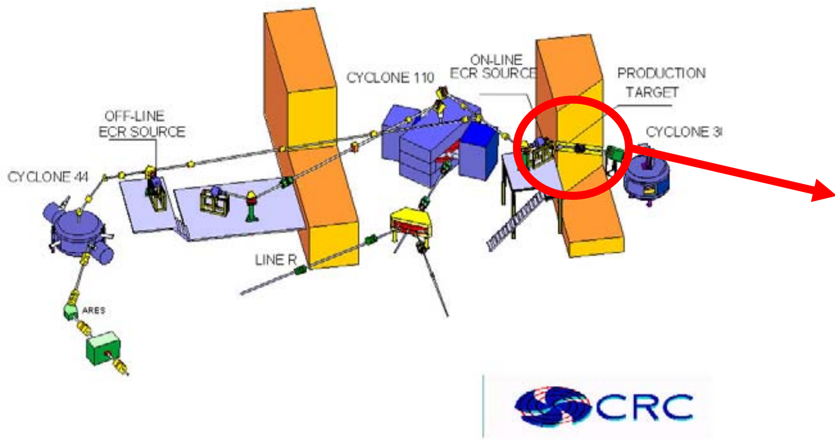
Converter technology:
(*J. Nolen, NPA 701 (2002) 312c*)

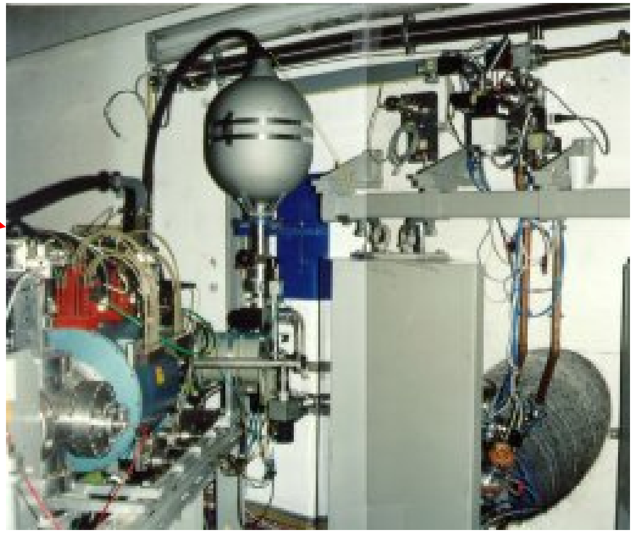




- **Converter technology preferred to direct irradiation (heat transfer and efficient cooling allows higher power compared to insulating BeO).**
- **^{6}He production rate is ~2x10^{13} ions/s (dc) for ~200 kW on target.**

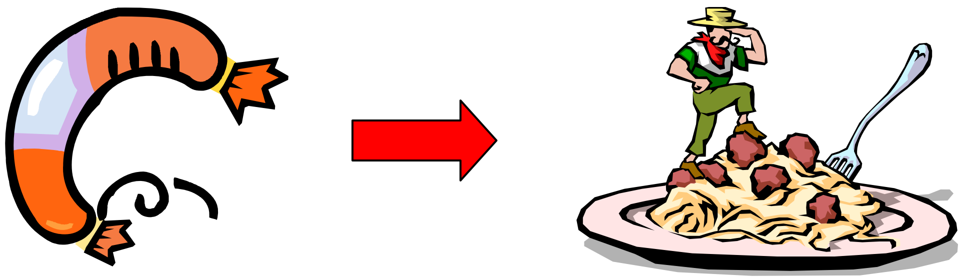
- Work within EURISOL task 2 to investigate production rate with "medical cyclotron"
  - Louvain-La-Neuve, M. Loislet





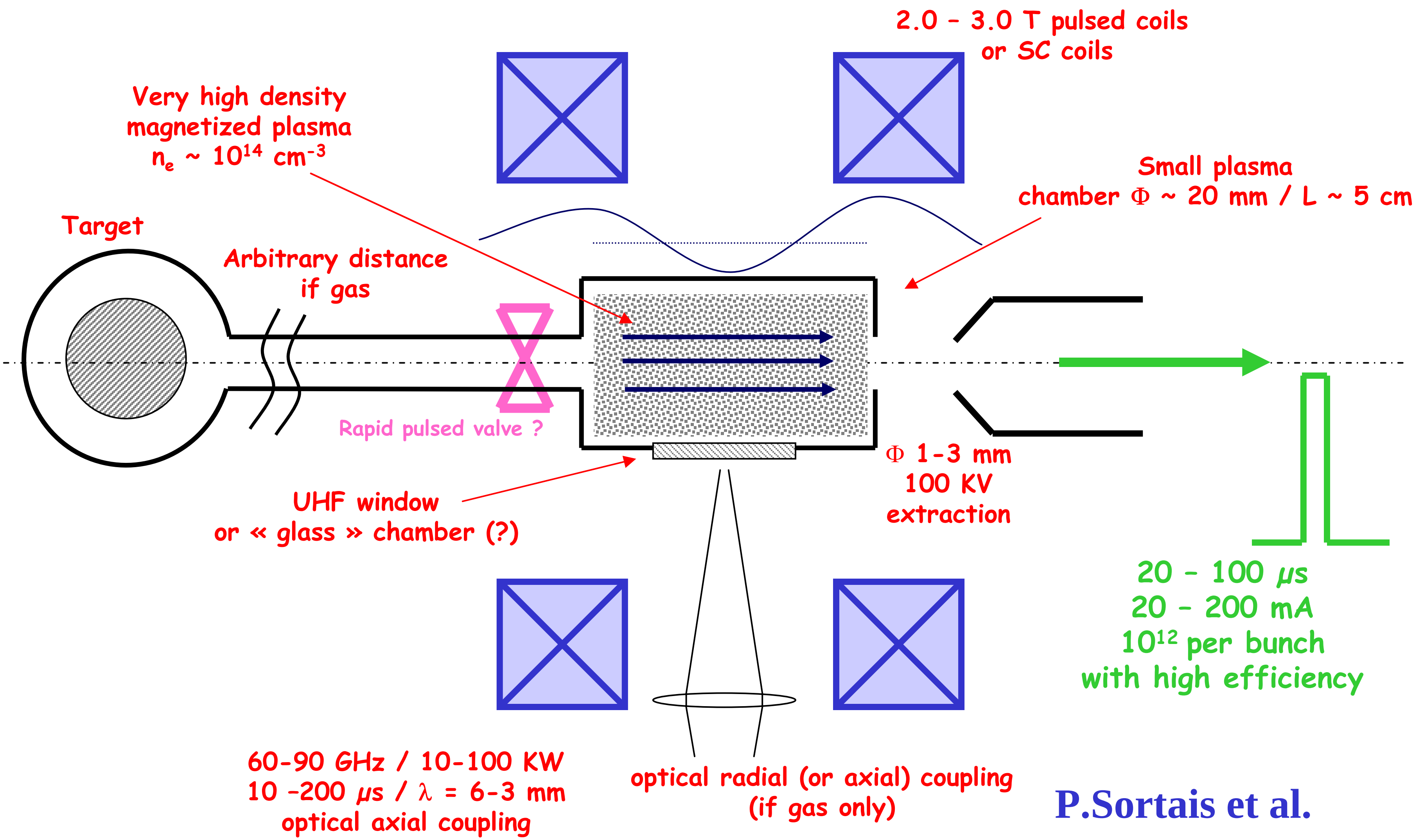
Low duty cycle, from dc to very short bunches…

- …or how to make meatballs out of sausages!



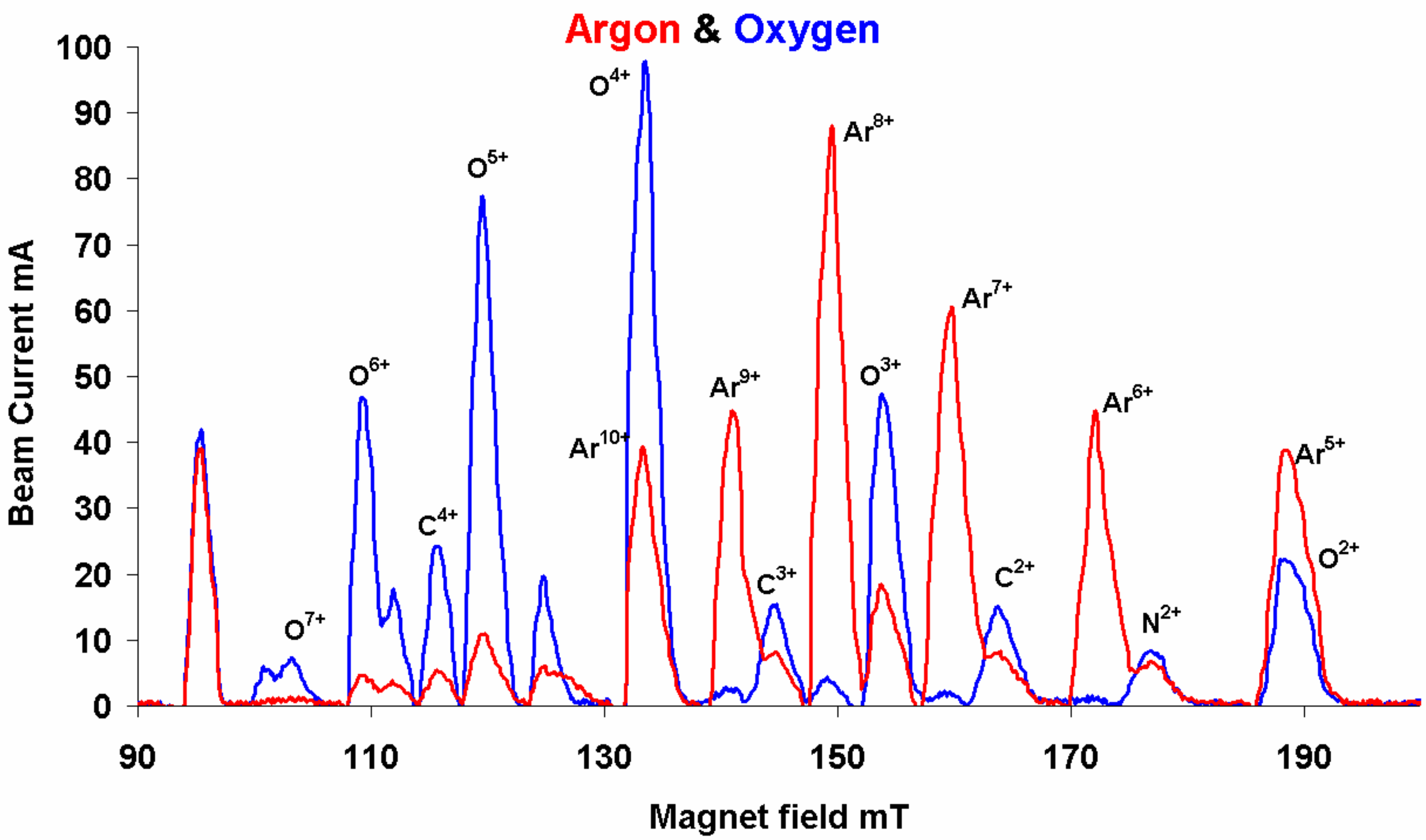
•Radioactive ions are usually produced as a "dc" beam but synchrotrons can only accelerate bunched beams.
•For high energies, linacs are long and expensive, synchrotrons are cheaper and more efficient.

60 GHz « ECR Duoplasmatron » for gaseous RIB

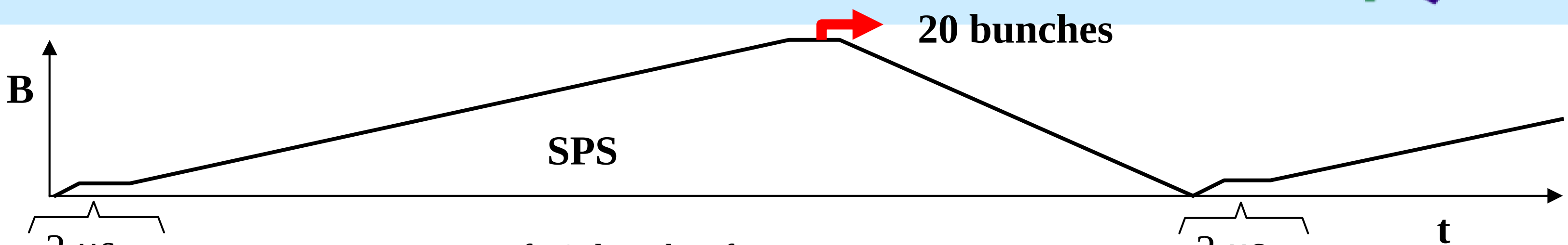


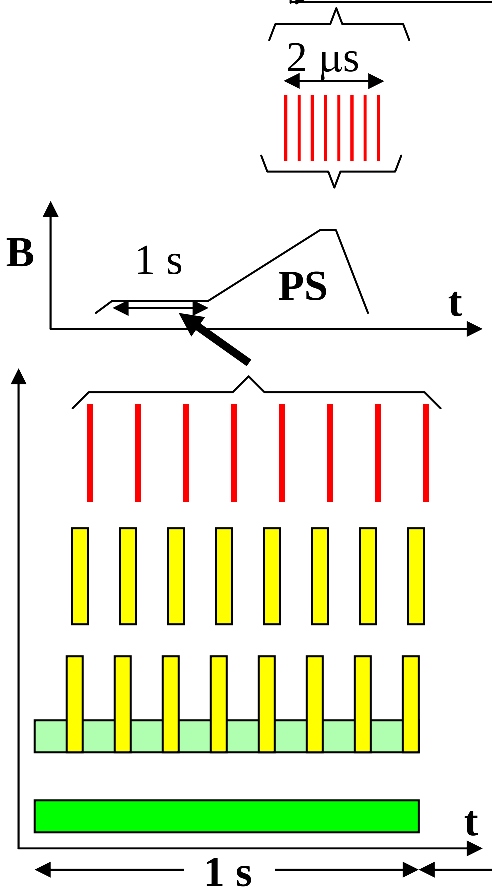
P.Sortais et al.

Charge state distribution!



From dc to very short bunches





SPS: injection of 20 bunches from PS.
Acceleration to decay ring energy and ejection.

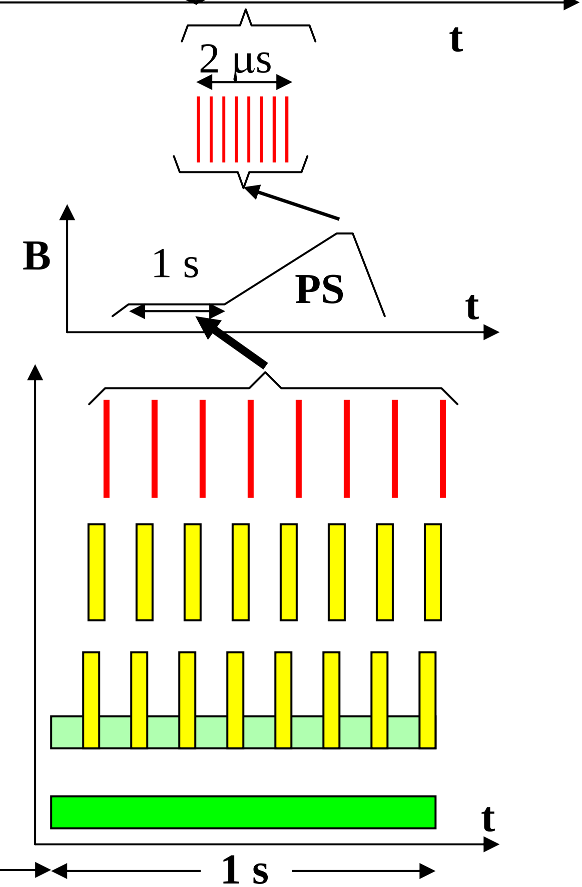
PS: 1 s flat bottom with 20 injections. Acceleration in ~1 s to ~86.7 Tm..

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

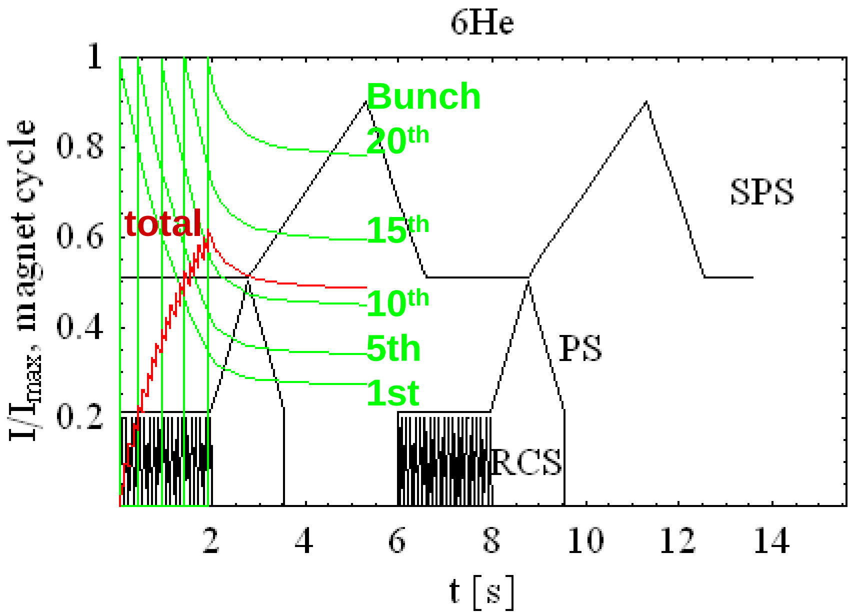
Post accelerator linac:
acceleration to ~100 MeV/u.
20 repetitions during 1 s.

60 GHz ECR: accumulation for 1/20 s ejection of fully stripped ~50 µs pulse.
20 batches during 1 s.

Target: dc production during 1 s.



Intensity evolution during acceleration



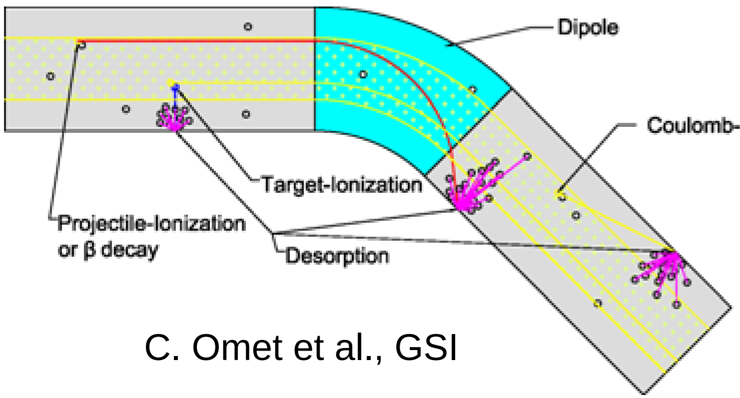
Cycle optimized for neutrino rate towards the detector

- 30% of first ^{6}He bunch injected are reaching decay ring
- Overall only 50% (^{6}He) and 80% (^{18}Ne) reach decay ring

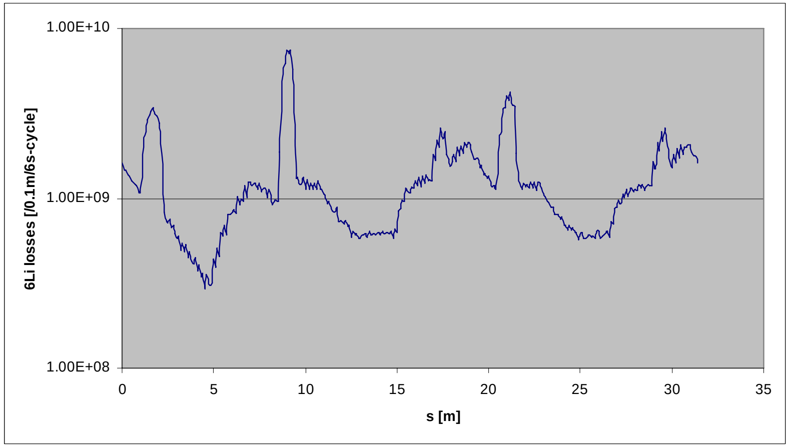
- Normalization
  - Single bunch intensity to maximum/bunch
  - Total intensity to total number accumulated in RCS

Dynamic vacuum

- Decay losses cause degradation of the vacuum due to desorption from the vacuum chamber

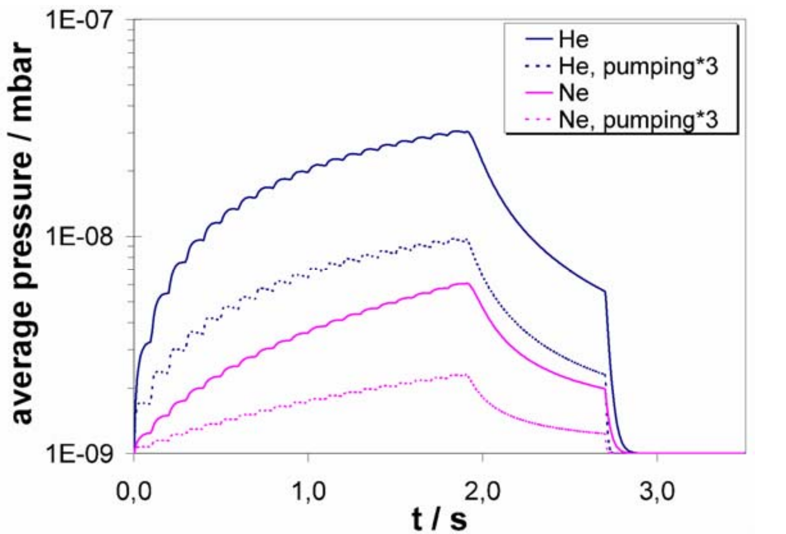


C. Omet et al., GSI



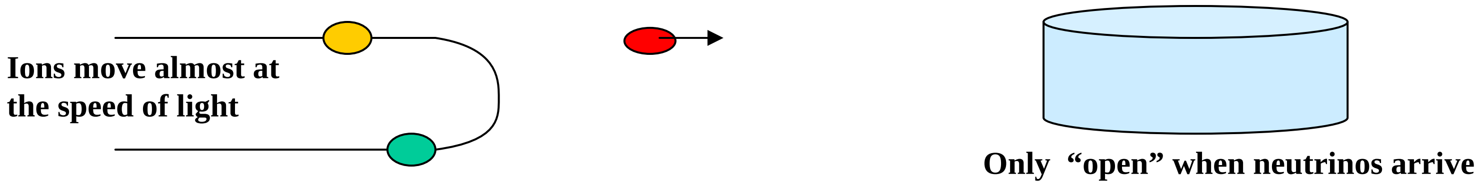
- The current study includes the PS, which does not have an optimized lattice for unstable ion transport and has no collimation system
  - The dynamic vacuum degrades to $3*10^{-8}$ Pa in steady state (^{6}He)

- An optimized lattice with collimation system would improve the situation by more than an order of magnitude.



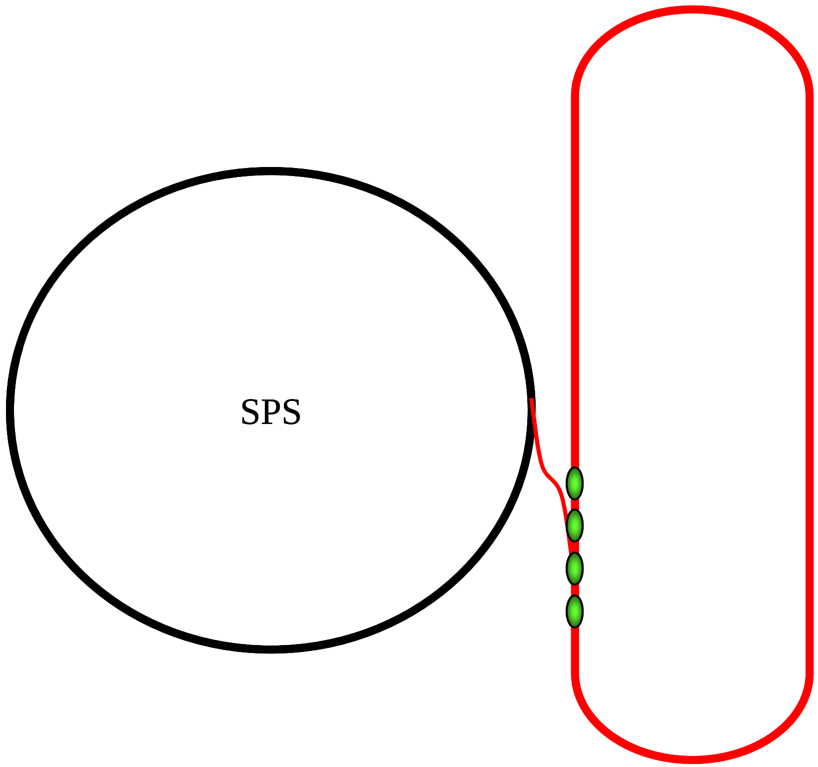
P. Spiller et al., GSI

- The atmospheric neutrino background is large at 500 MeV, the detector can only be open for a short moment every second
  - The decay products move with the ion bunch which results in a bunched neutrino beam



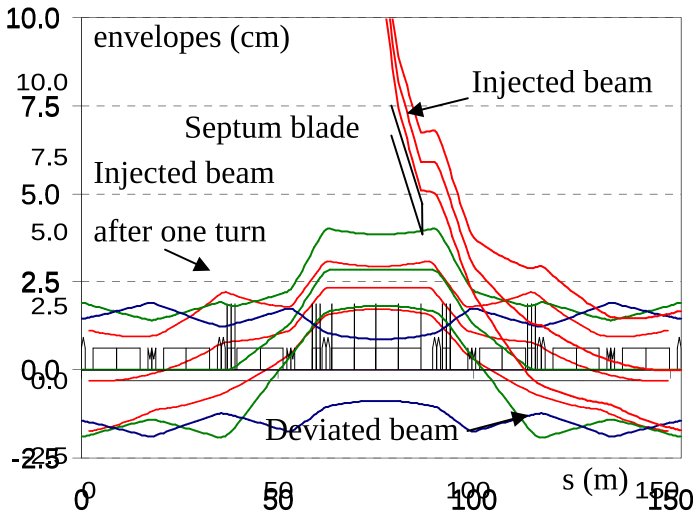
  - Low duty cycle – short and few bunches in decay ring
  - Accumulation to make use of as many decaying ions as possible from each acceleration cycle

- Ejection to matched dispersion trajectory
- Asymmetric bunch merging

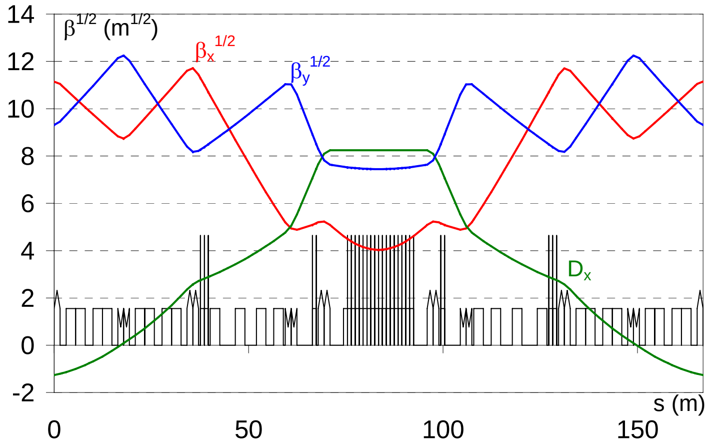


Injection

Horizontal envelopes at injection

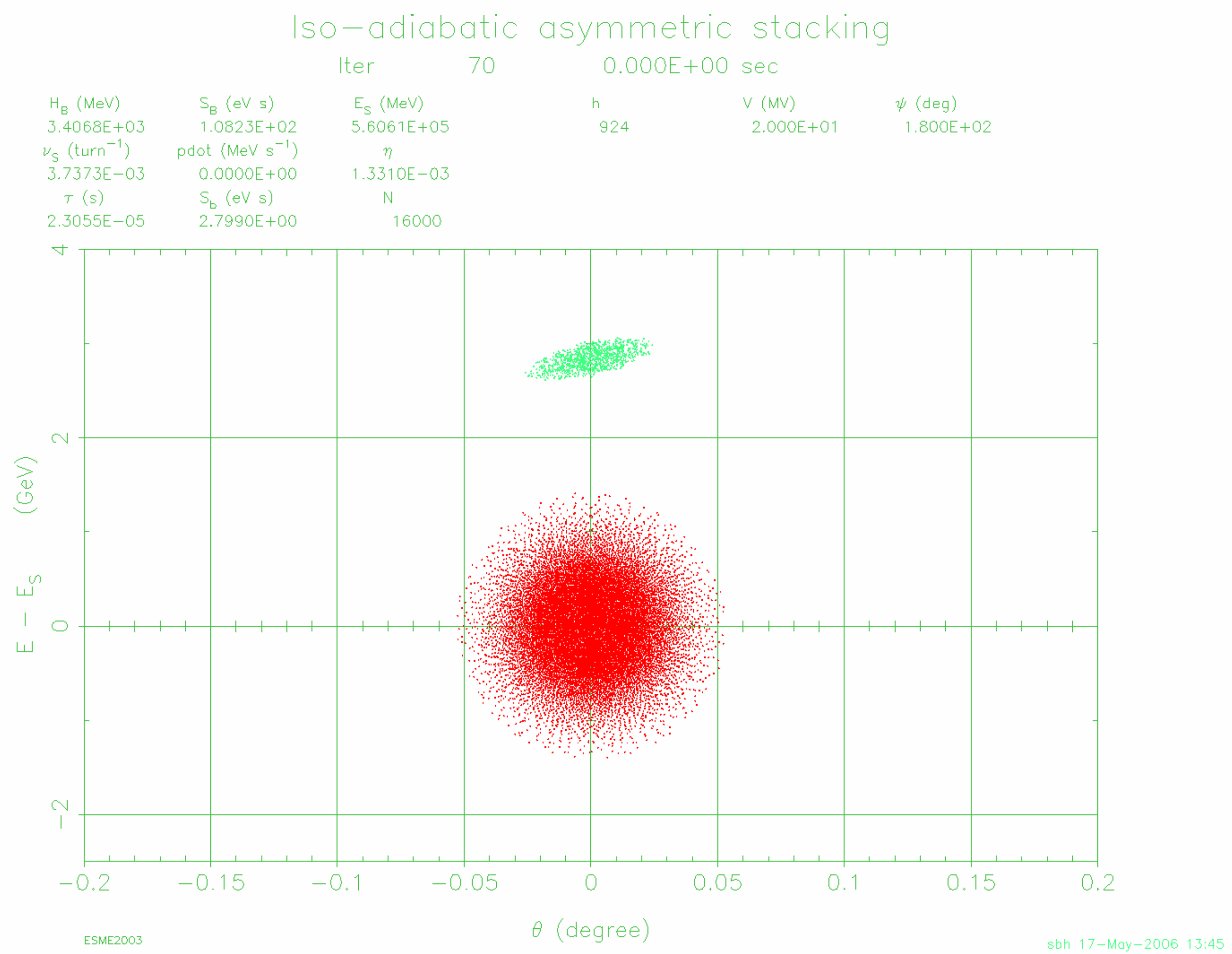


Optical functions in the injection section



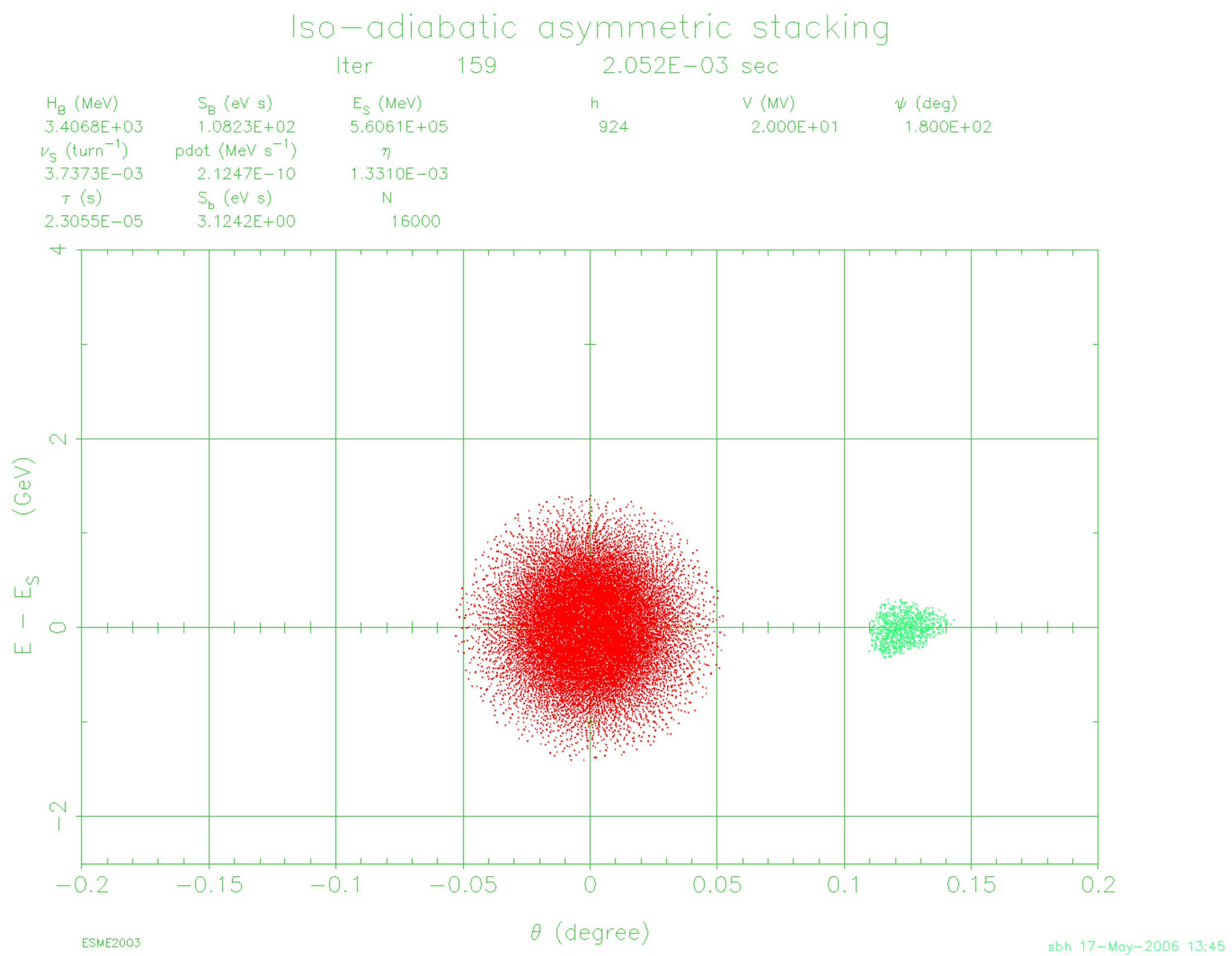
- Injection is located in a dispersive area
- The stored beam is pushed near the septum blade with 4 “kickers”. At each injection, a part of the beam is lost in the septum
- Fresh beam is injected off momentum on its chromatic orbit. “Kickers” are switched off before injected beam comes back
- During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

Injection



Iso−adiabatic asymmetric stacking
Iter 70 0.000E+00 sec
H_B (MeV) 3.4068E+03
S_B (eV s) 1.0823E+02
E_S (MeV) 5.6061E+05
h 924
V (MV) 2.000E+01
ψ (deg) 1.800E+02
ν_S (turn^−1) 3.7373E−03
pdot (MeV s^−1) 0.0000E+00
η 1.3310E−03
τ (s) 2.3055E−05
S_b (eV s) 2.7990E+00
N 16000
E − E_S (GeV)
θ (degree)
−0.2
−0.15
−0.1
−0.05
0
0.05
0.1
0.15
0.2
4
2
0
−2
ESME2003
sbh 17−May−2006 13:45

Rotation



Iso-adiabatic asymmetric stacking
Iter 159 2.052E-03 sec
H_B (MeV) 3.4068E+03
S_B (eV s) 1.0823E+02
E_S (MeV) 5.6061E+05
h 924
V (MV) 2.000E+01
ψ (deg) 1.800E+02
ν_S (turn^-1) 3.7373E-03
pdot (MeV s^-1) 2.1247E-10
η 1.3310E-03
τ (s) 2.3055E-05
S_b (eV s) 3.1242E+00
N 16000
E − E_S (GeV)
θ (degree)
ESME2003
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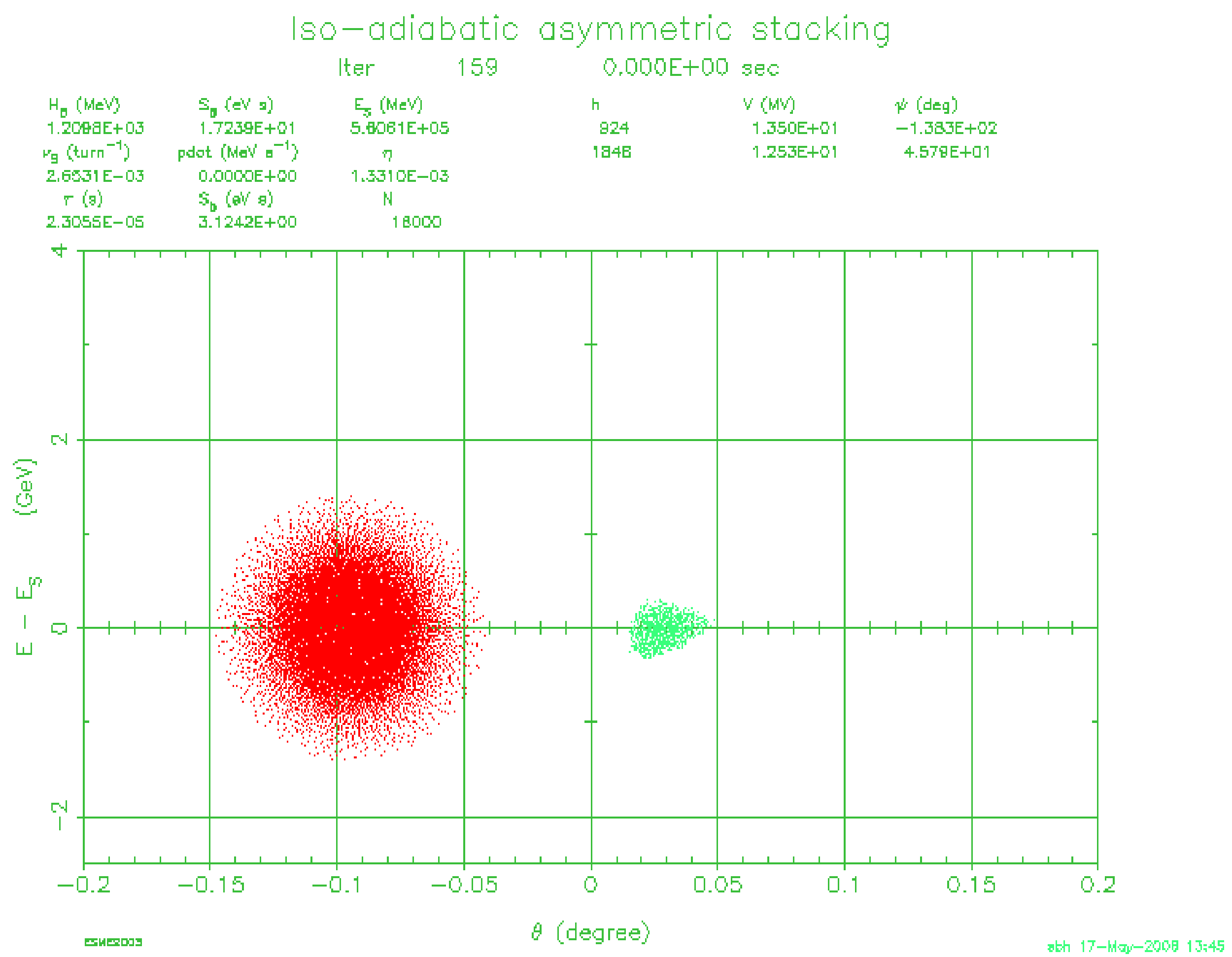
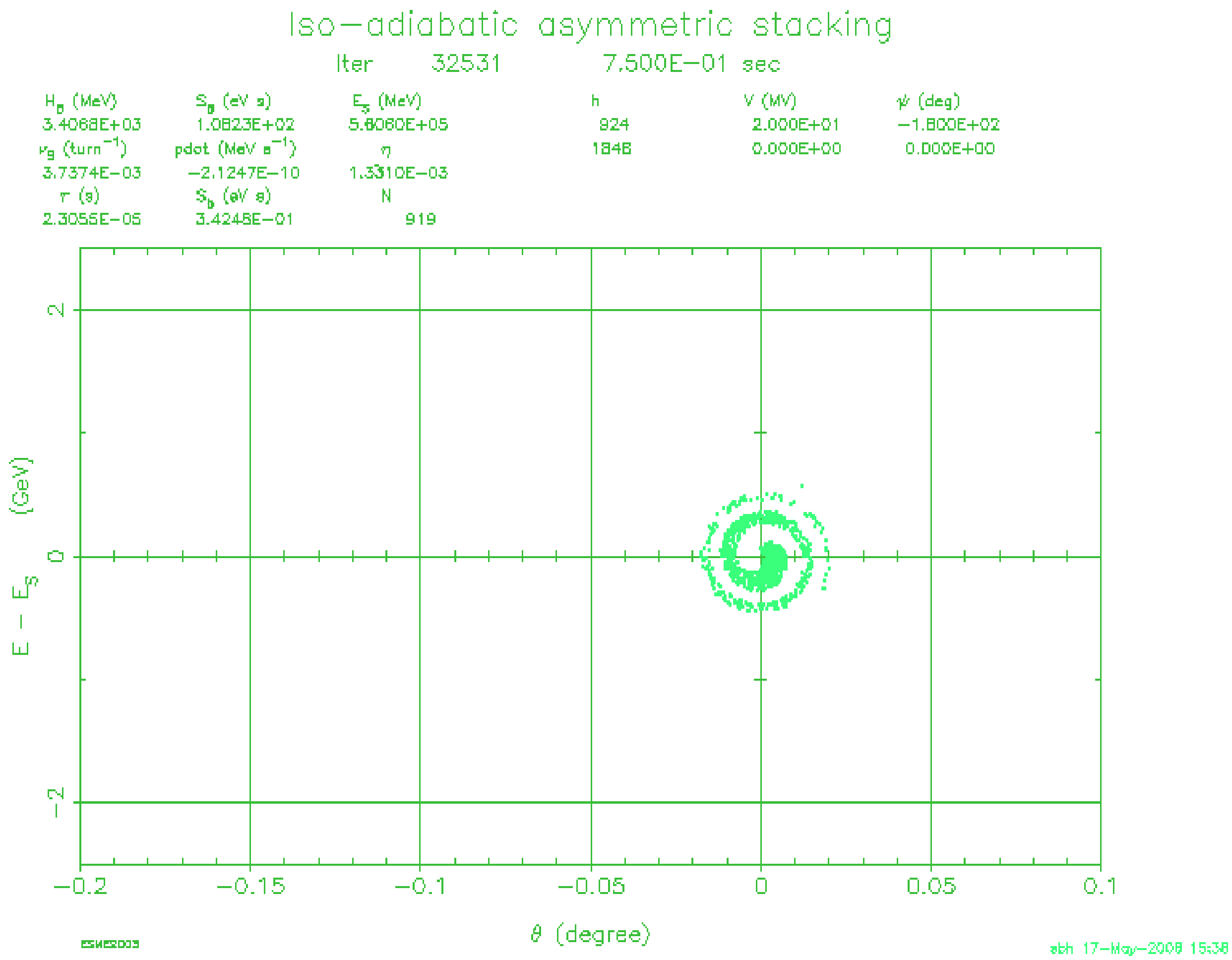
Merging

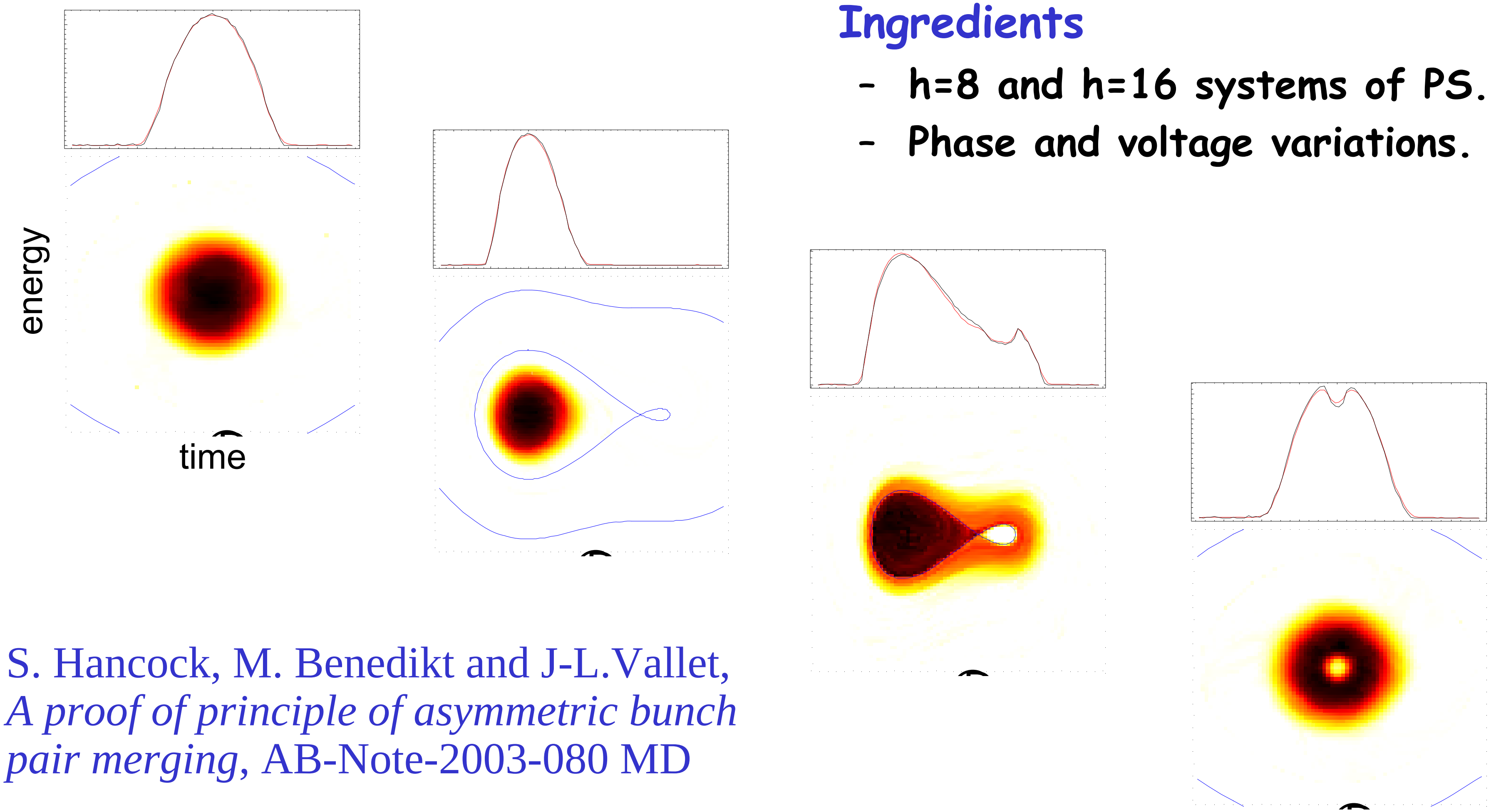


Iso−adiabatic asymmetric stacking
Iter 159 0.000E+00 sec
H_B (MeV) 1.2098E+03
S_B (eV s) 1.7239E+01
E_s (MeV) 5.6061E+05
h 924 1848
V (MV) 1.350E+01 1.253E+01
ψ (deg) −1.383E+02 4.579E+01
ν_s (turn^−1) 2.6531E−03
pdot (MeV s^−1) 0.0000E+00
η 1.3310E−03
τ (s) 2.3055E−05
S_b (eV s) 3.1242E+00
N 18000
E − E_s (GeV)
θ (degree)
−0.2 −0.15 −0.1 −0.05 0 0.05 0.1 0.15 0.2
−2 0 2 4
ESME2003
abh 17−May−2008 13:45

Repeated Merging



Test experiment in CERN PS



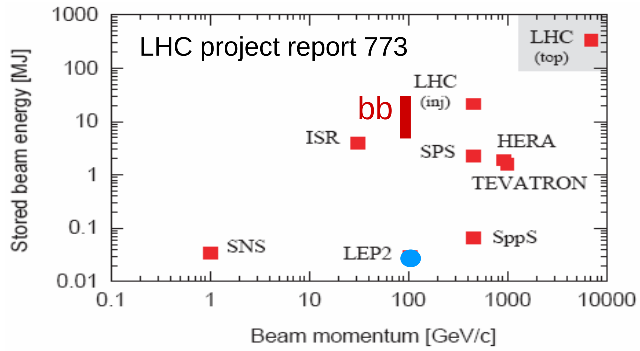
Ingredients

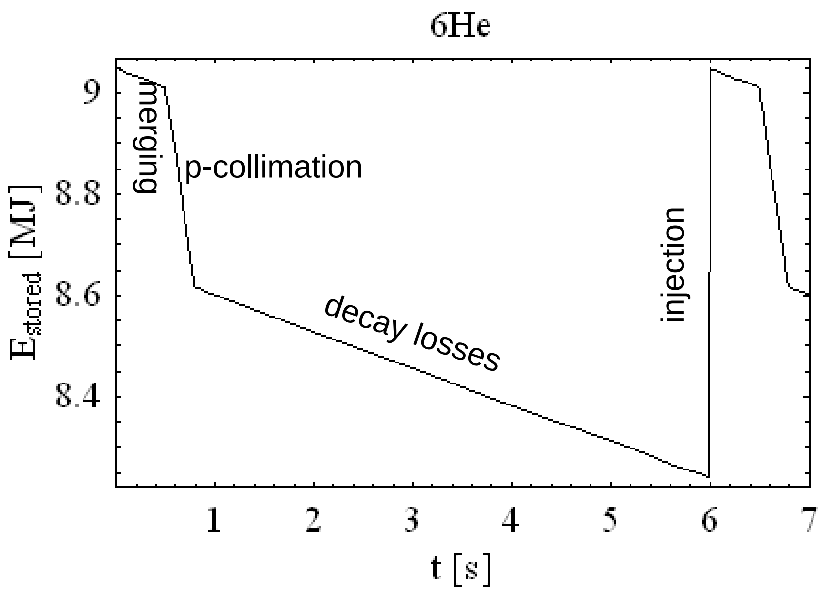
- h=8 and h=16 systems of PS.
- Phase and voltage variations.

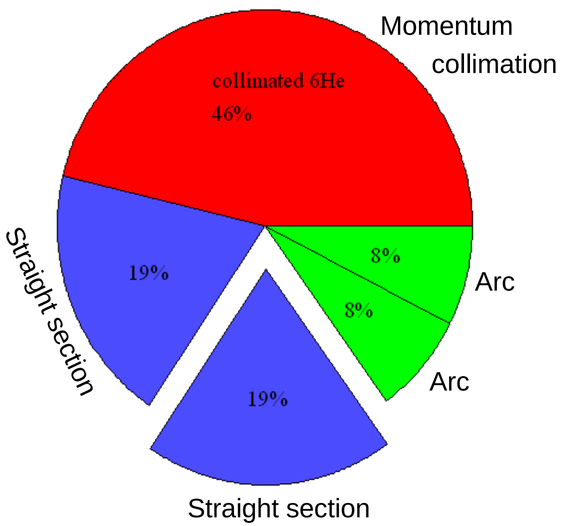
S. Hancock, M. Benedikt and J-L.Vallet, *A proof of principle of asymmetric bunch pair merging*, AB-Note-2003-080 MD

Particle turnover

- ~1 MJ beam energy/cycle injected
  → equivalent ion number to be removed
  ~25 W/m average



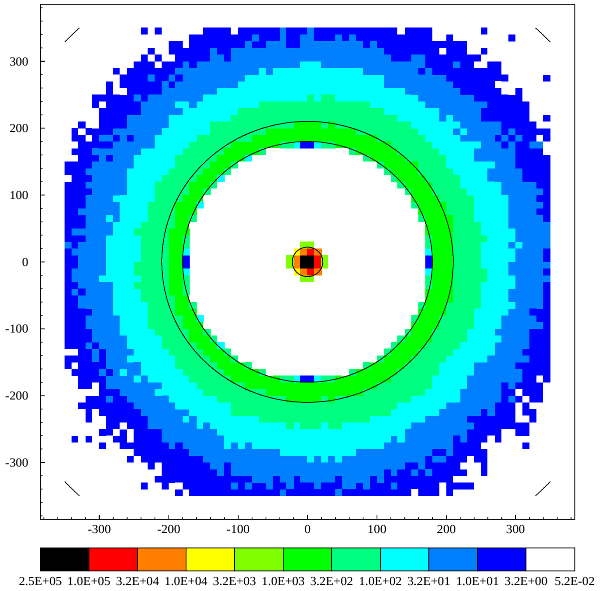




- Momentum collimation: ~5*10^{12} ^{6}He ions to be collimated per cycle
- Decay: ~5*10^{12} ^{6}Li ions to be removed per cycle per meter

Decay losses

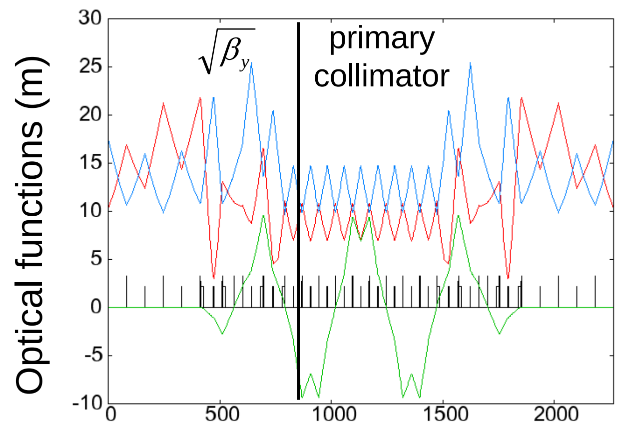
- **Losses during acceleration**
  - Full FLUKA simulations in progress for all stages (M. Magistris and M. Silari, *Parameters of radiological interest for a beta-beam decay ring*, TIS-2003-017-RP-TN).
- **Preliminary results:**
  - Manageable in low-energy part.
  - PS heavily activated (1 s flat bottom).
    - 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)

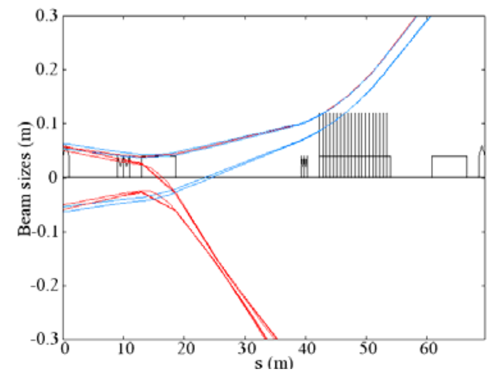
Collimation and absorption

- **Merging:**
  - increases longitudinal emittance
  - Ions pushed outside longitudinal acceptance
    $\rightarrow$ momentum collimation
    in straight section

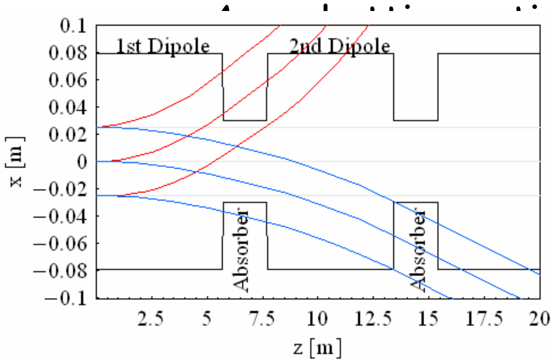


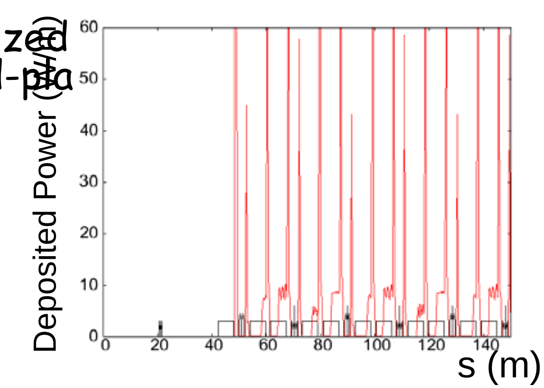
Straight section:

Ion extraction et each end



- **Decay product**
  - Daughter ion occurring continuously along decay ring
  - To be avoided:
    - magnet quenching: reduce particle deposition (average 10 W/m)
    - Uncontrolled activation





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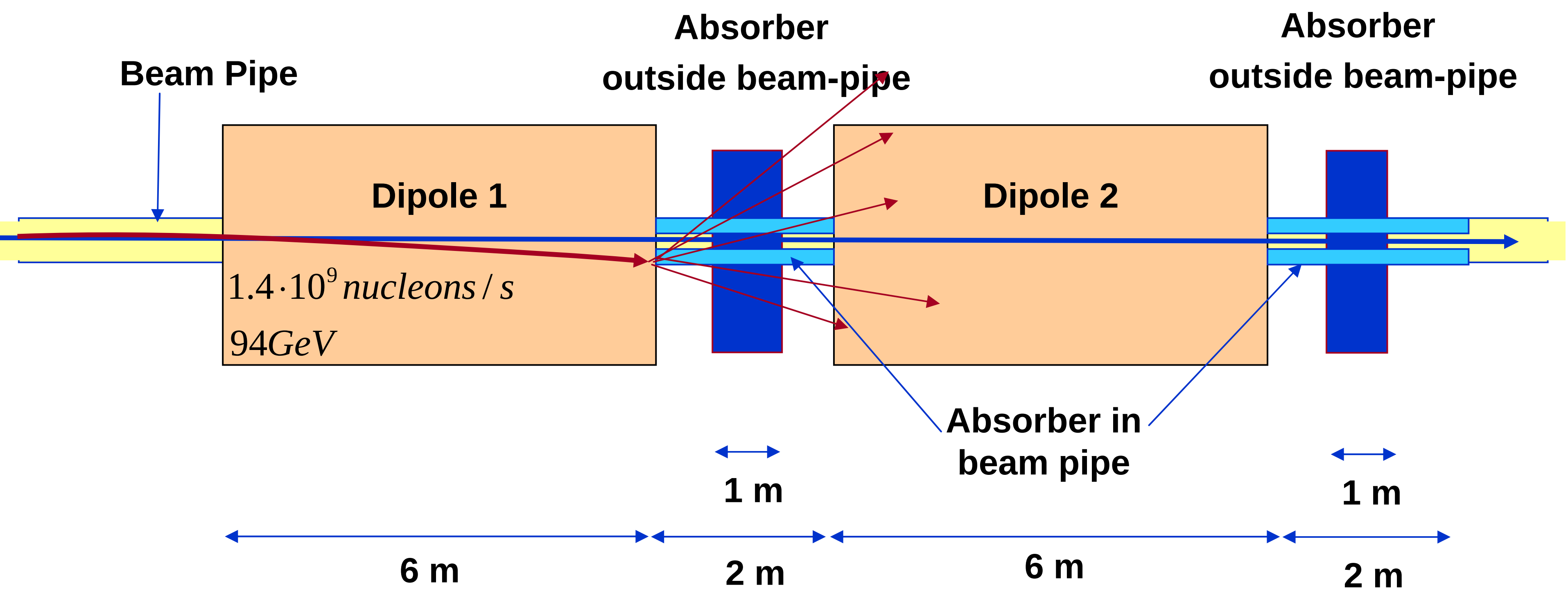
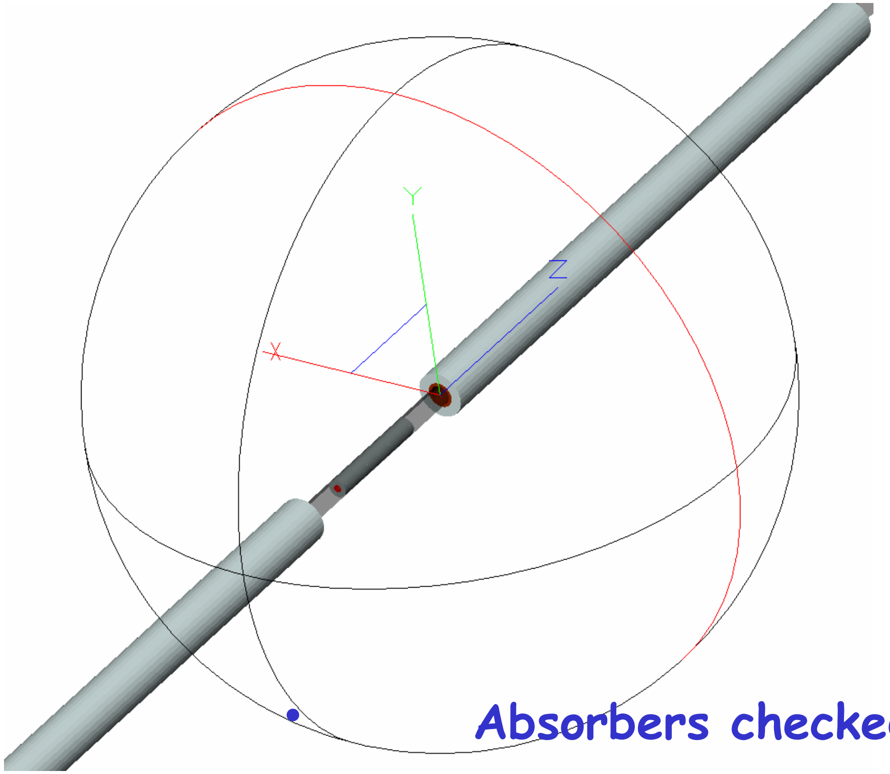
A. Chance et al., CEA Saclay

Model for absorbers

Horizontal Plane



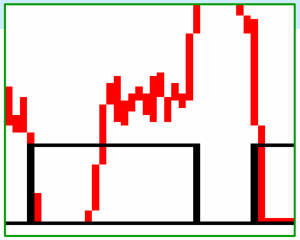
Decay ring magnet protection

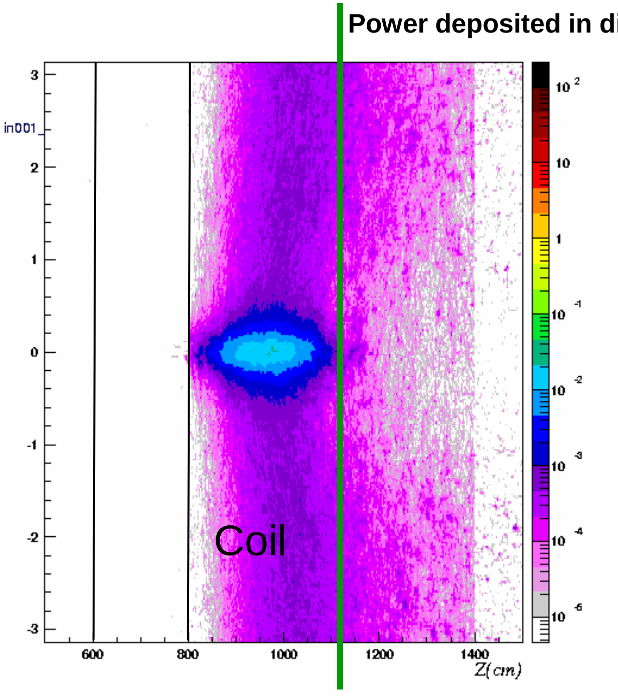


- Absorbers checked (in beam pipe):
- No absorber, Carbon, Iron, Tungsten

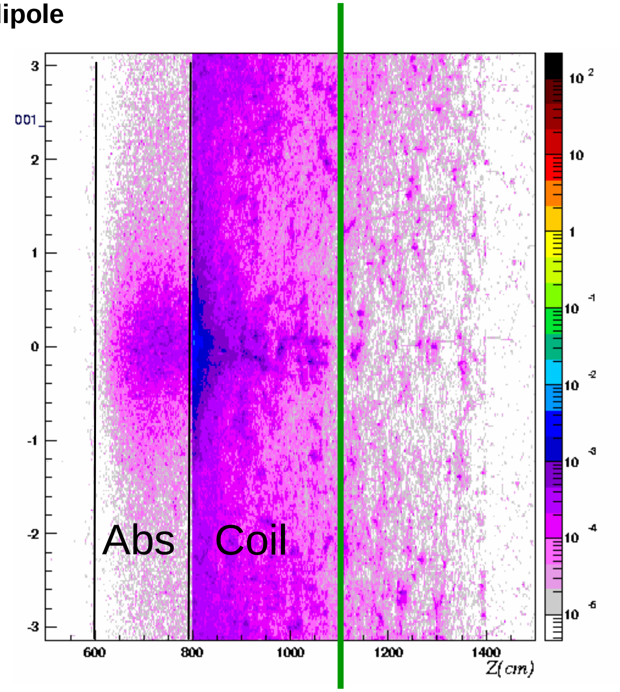
Theis C., et al.:
"Interactive three dimensional visualization and creation of geometries for Monte Carlo calculations", Nuclear Instruments and Methods in Physics Research A 562, pp. 827-829 (2006).

Longitudinal penetration in coil

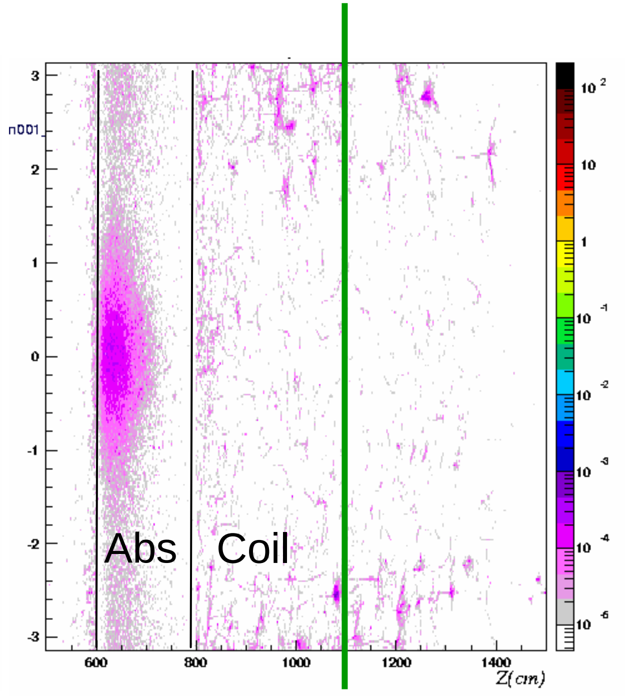




No absorber

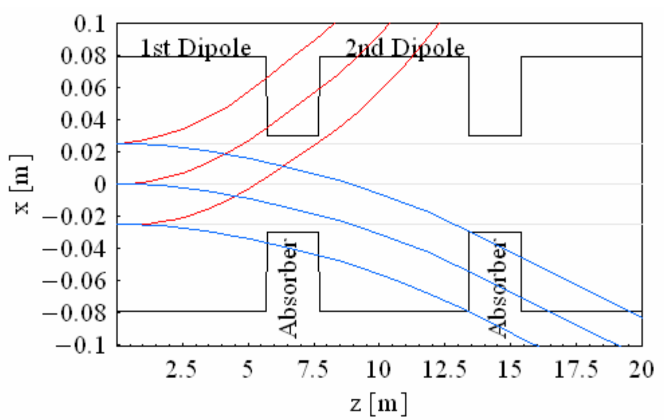


Carbon



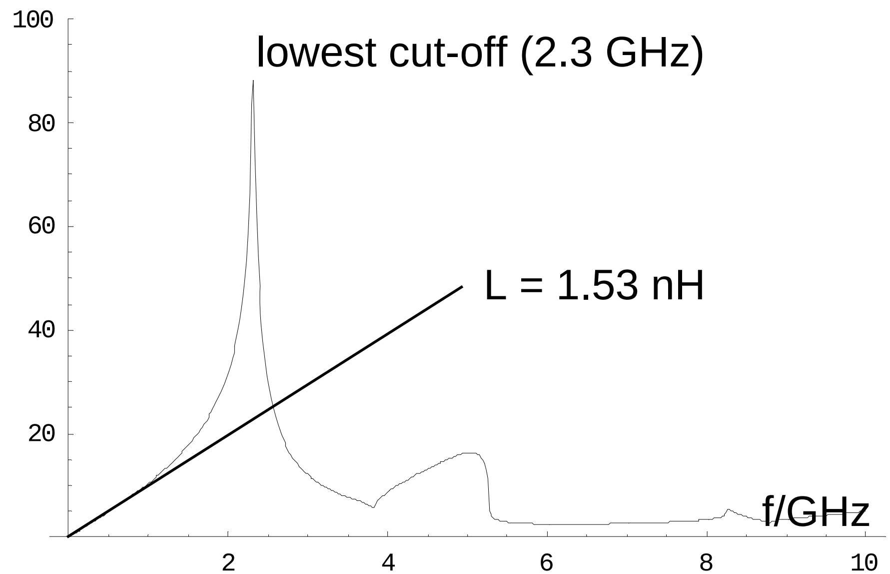
Stainless Steel

Impedance, 340 steps!

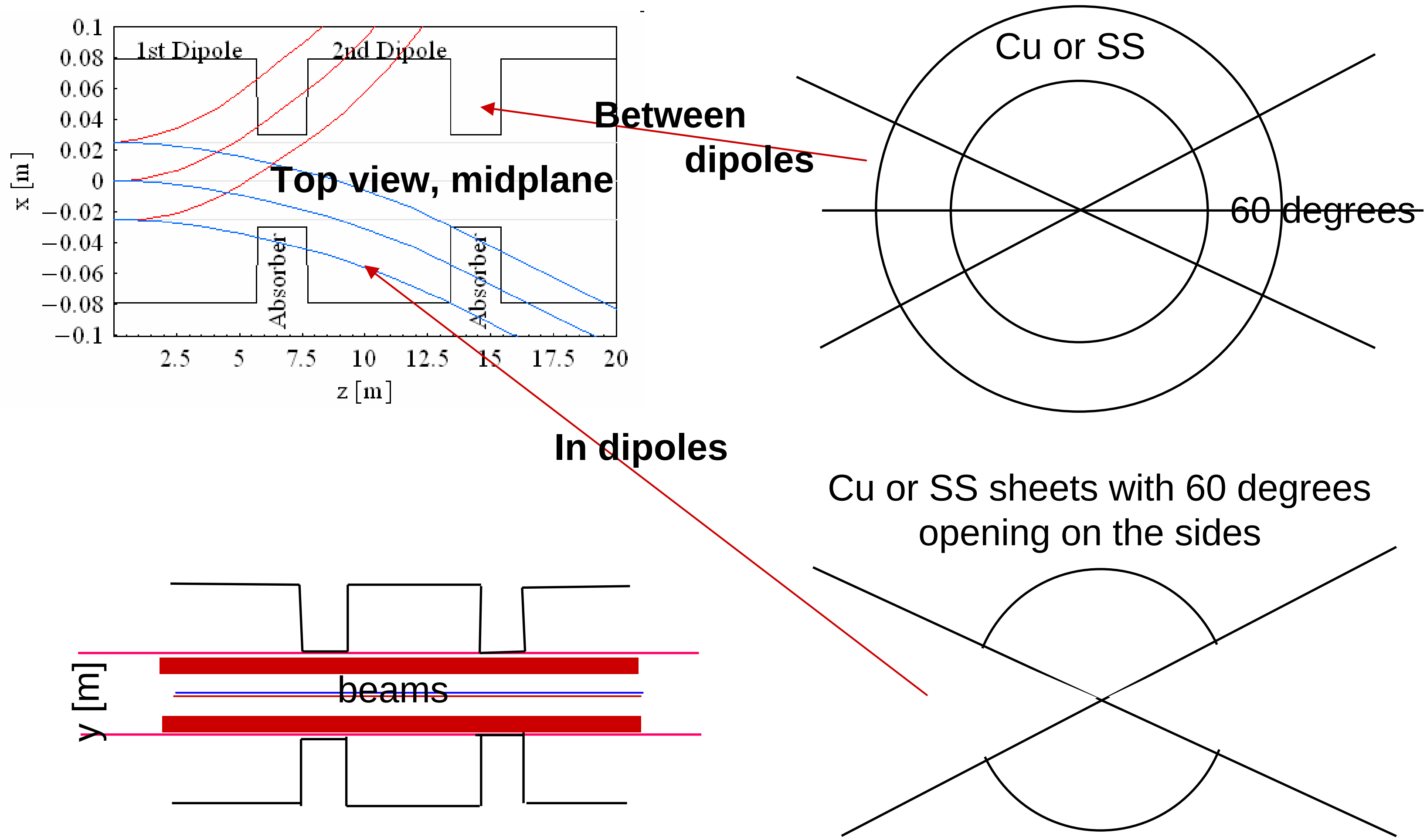


Below 2.3 GHz, a total of 340 steps (170 absorbers) would add up to 0.5 μH, which seems really high.

Impedance of one step (diameter 6 to 10 cm or 10 to 6 cm):



Possible new solution



Results for heat deposition

Quantity / Absorb material	Max Heat [mWatt/cm^3]	Dist from Dipole Entry [cm]	Angle for max [degrees]
Vacuum	> 30	~ 200	~ 0
Carbon	1.4	20	7
Stainless Steel	0.4 (stat)	-	-
Tungsten	0.2 (stat)	-	-

Value for LHC Magnet > 4.5 mWatt/cm^3 : we have margin, load line more favorable, cooling channels possible to introduce.

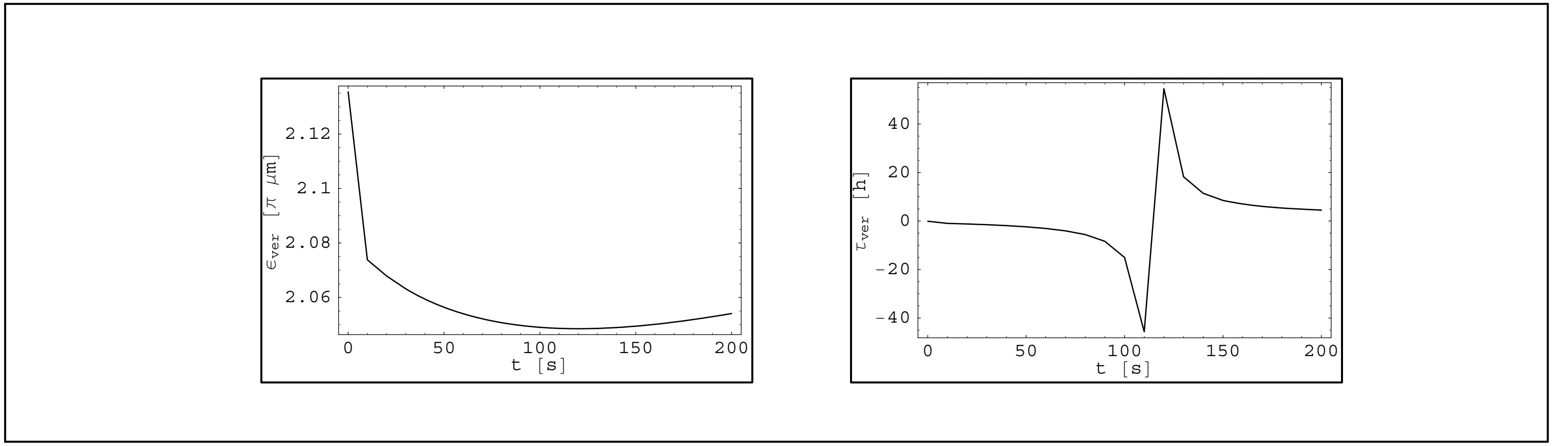
Next step: Complete heat deposition and shielding calculations with detailed decaying beam (tracking studies)

Intra Beam scattering, growth times

Results obtained with Mad-8

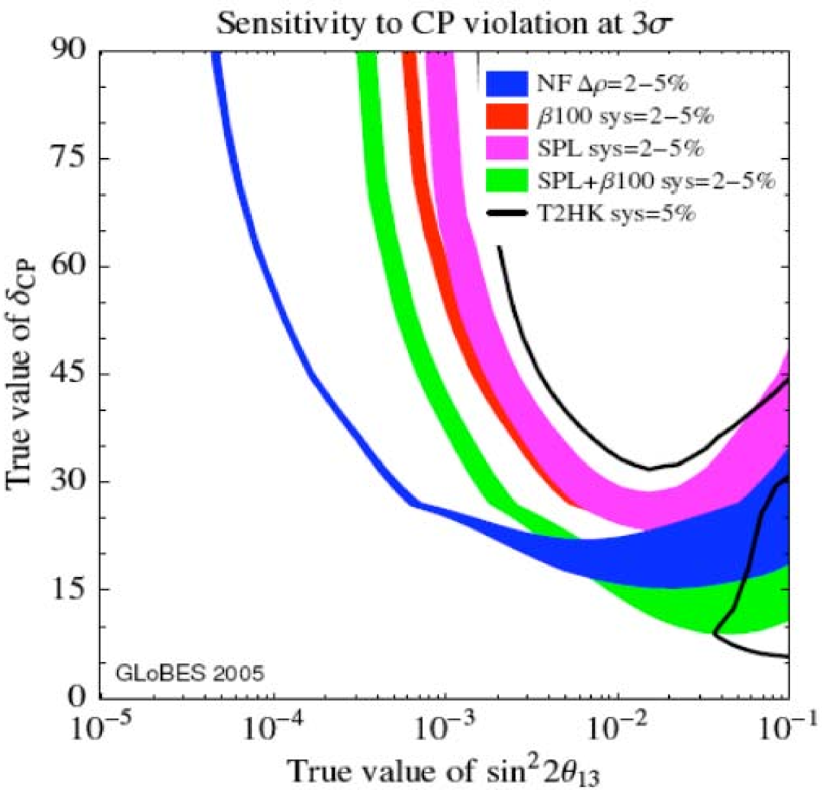
- ^{6}He

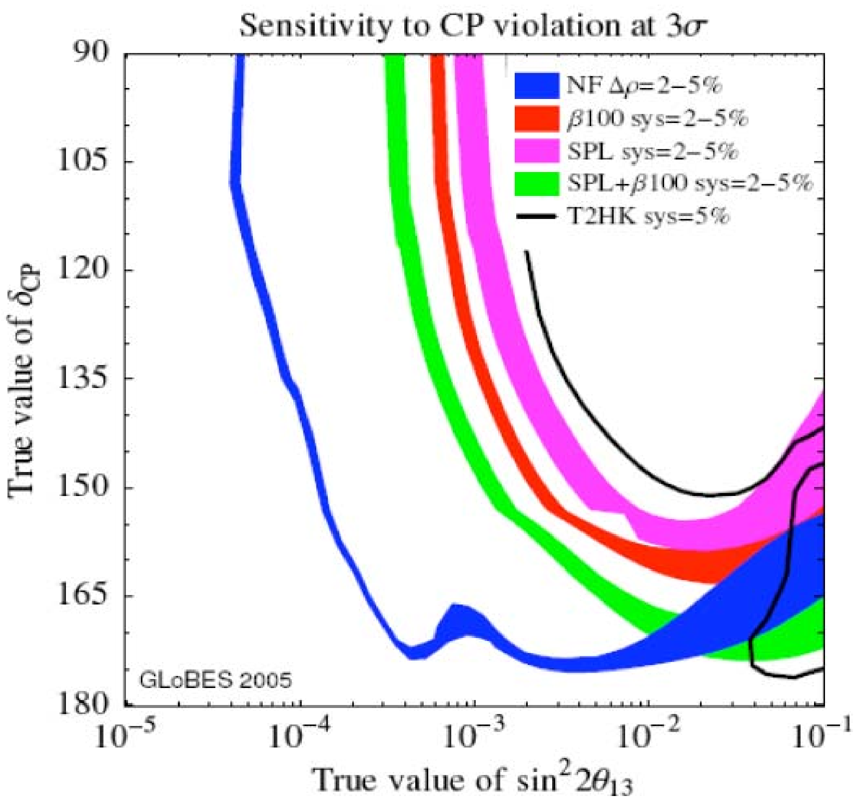
	RCS	PS	SPS	DECAY
τ_{long}[s]	22	194	3289	263345
τ_{hor}[s]	-10361	-3157	-111774	44566
τ_{ver}[s]	-4840	-5082	-214853	5605307



And what next?

•





Production

	Nominal production rate [ions/s]	Required production rate [ions/s]	Missing factor
6He	2×10^{13}	2×10^{13}	1
18Ne	8×10^{11}	1.9×10^{13}	24

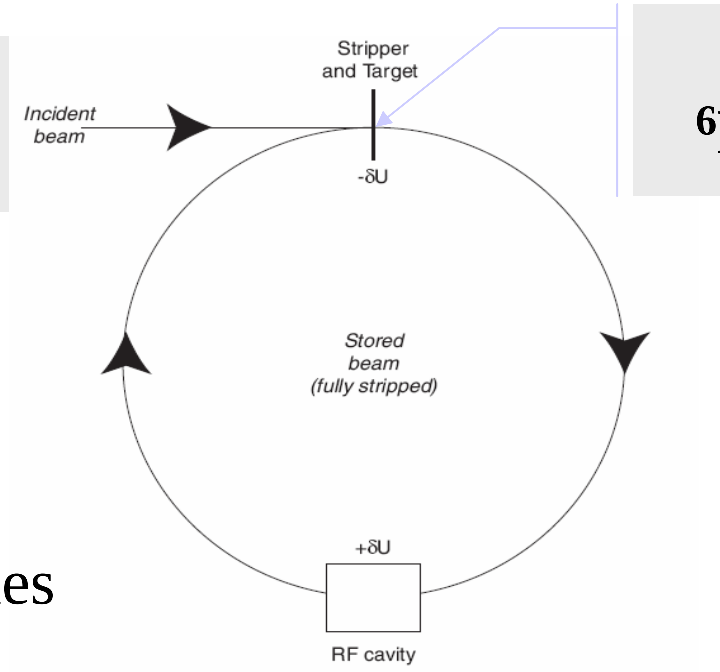
- Major challenge for ^{18}Ne
- Encouraging results for direct production at LLN ^{3}He(^{16}O,n)^{18}Ne
- New production method proposed by Y. Mori and C. Rubbia!

A new approach for the production

Beam cooling with ionisation losses – C. Rubbia, A Ferrari, Y. Kadi and V. Vlachoudis in NIM A 568 (2006) 475–487

"Many other applications in a number of different fields may also take profit of **intense beams of radioactive ions**."

^{7}Li
^{6}Li



$^{7}Li(d,p)^{8}Li$
$^{6}Li(^{3}He,n)^{8}B$

Missed opportunities

See also: Development of FFAG accelerators and their applications for intense secondary particle production, Y. Mori, NIM A562(2006)591

Very advanced gas target in paper by C. Rubbia et al.

- The gas jet target may follow the principle of a Supersonic Gas Injector (SGI) implemented for fuelling and diagnostics of high-temperature fusion plasma in several Tokamak, NSTX (USA), Tore Supra (France), HT-& and HL-1M (China), normally operated with H^2, D^2 and He gases.
- The volume of gas (at 250 Torr) is about 4.3 m^3/s, corresponding to 7,46 x 10^{25} atoms/s or 248 g/s.

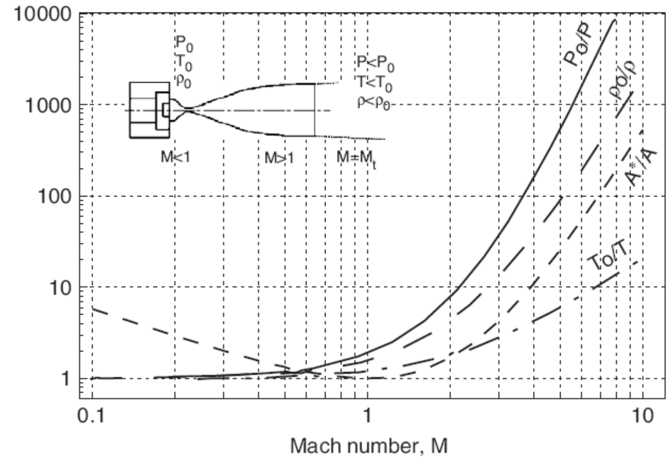
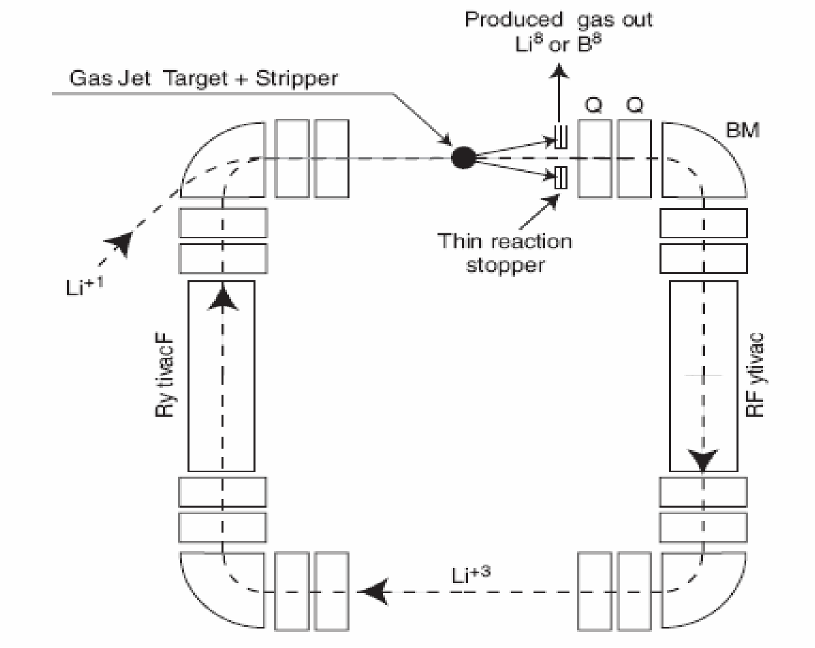
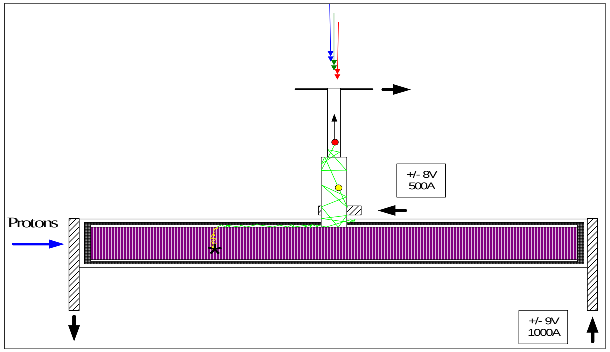


Fig. 9. Isentropic behaviour of a supersonic Laval nozzle with convergent and divergent contours.

Collection using "a catcher" in paper by Carlo Rubbia et al.

"The technique of using very thin targets in order to produce secondary neutral beams has been in use for many years. Probably the best known and most successful source of radioactive beams is ISOLDE."

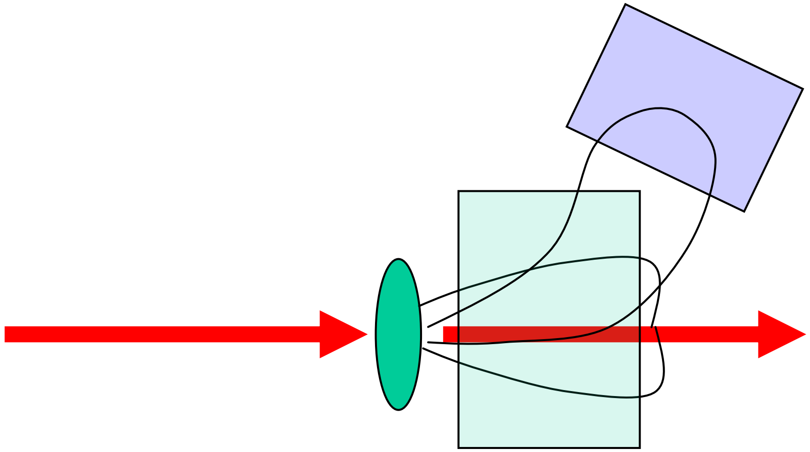


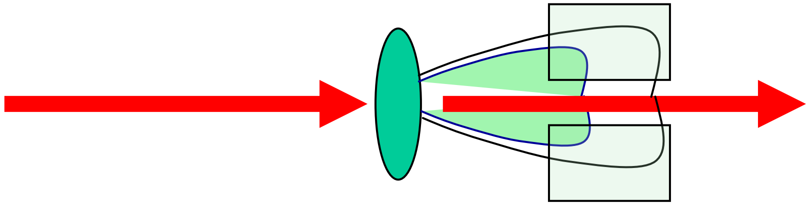


B form compounds and has never been produced in from a solid ISOL target. Can we use "Flourination" and extract BF_3?

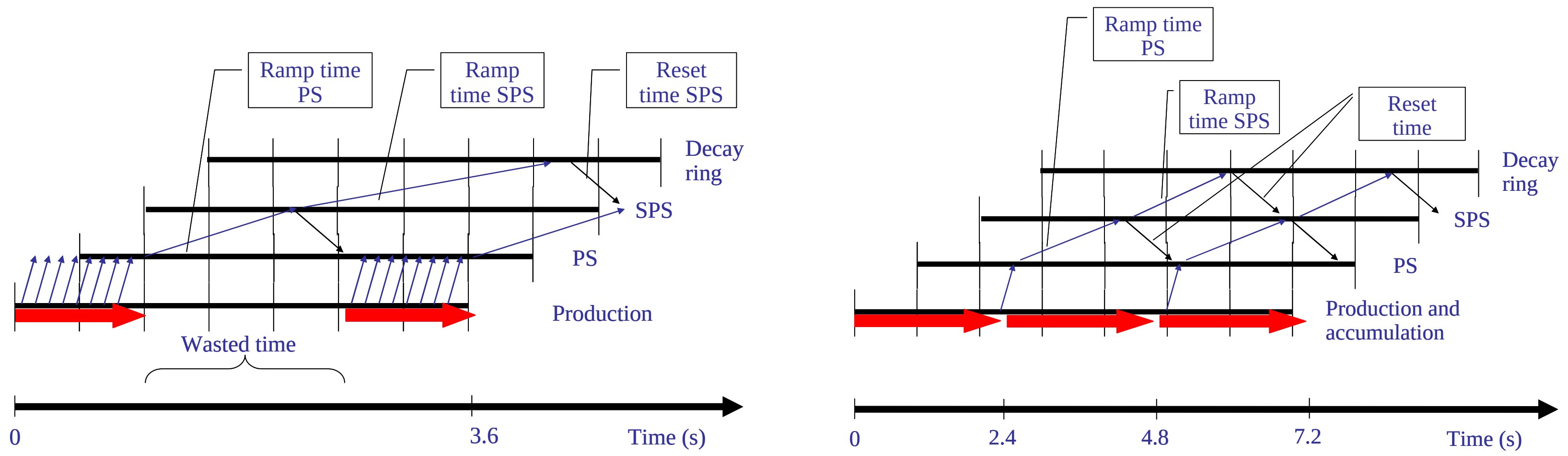
Problems with collection device

- A large proportion of beam particles (^6Li) will be scattered into the collection device.
  - The scattered primary beam intensity could be up to a factor of 100 larger than the RI intensity for 5-13 degree using a Rutherford scattering approximation for the scattered primary beam particles (M. Loislet, UCL)
  - The ^8B ions are produced in a cone of 13 degree with 20 MeV ^6Li ions with an energy of 12 MeV±4 MeV (33% !).



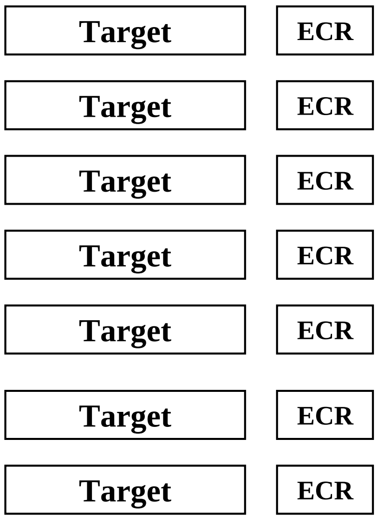


Why do we gain with such an accumulation ring?

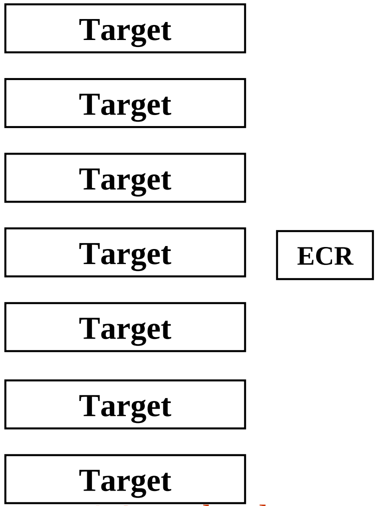


- Left: Cycle without accumulation
- Right: Cycle with accumulation. Note that we always produce ions in this case!

Multiple targets and ECR sources with accumulation ring

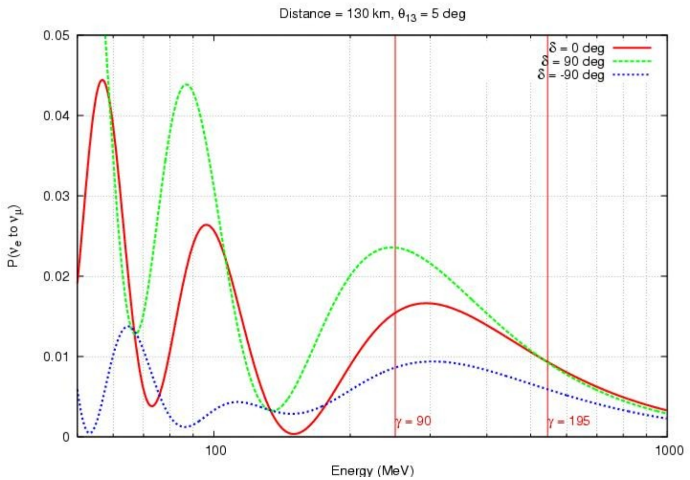


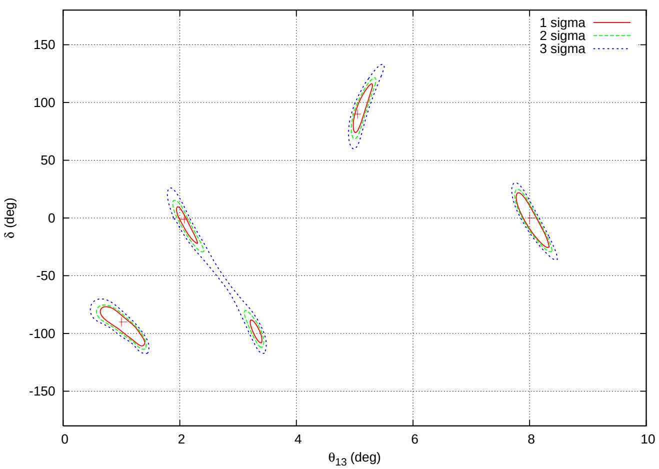
- Multiple target and multiple ECR sources
  - Proton beam split between 7 targets i.e. 1.4 MW of protons in total on all targets
  - 1 second accumulation time in the ECR source
  - 0.1 seconds between injections into linac and Accumulation ring
  - Accumulation of 10 bunches in SPS
  - ECR pulse: 2 10^{11} ions per pulse
  - Annual rate: 1 10^{18} (without accumulation ring 4 $10^{17)}$
  - Drawback: Expensive and complicated!



- Multiple target and single ECR sources
  - Proton beam split between 7 targets i.e. 1.4 MW of protons in total on all targets
  - 0.1 second accumulation time in the ECR source
  - 0.1 seconds between injections into linac and Accumulation ring
  - Accumulation of 10 bunches in SPS
  - ECR pulse: 1.4 10^{11} ions per pulse
  - Annual rate: 1 10^{18} (without accumulation ring 4 $10^{17)}$
  - Drawback: Efficiency in the transport from target to ECR!

EC: A monochromatic neutrino beam





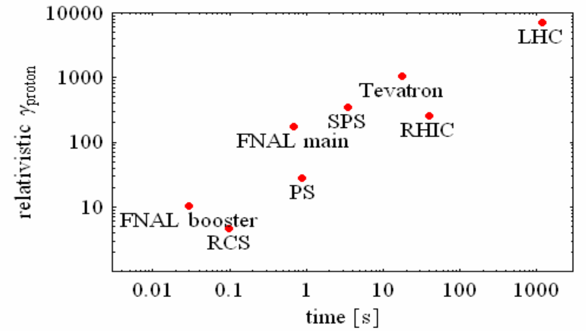
Decay	$T_{1/2}$	BR_ν	EC/ν	I^{β}_{EC}	B(GT)	E_{GR}	Γ_{GR}	Q_{EC}	E_ν	ΔE_ν
$^{148}Dy \rightarrow {}^{148}Tb^*$	3.1 m	1	0.96	0.96	0.46	620		2682	2062	
$^{150}Dy \rightarrow {}^{150}Tb^*$	7.2 m	0.64	1	1	0.32	397		1794	1397	
$^{152}Tm2^- \rightarrow {}^{152}E_T^*$	8.0 s	1	0.45	0.50	0.48	4300	520	8700	4400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

Long half life - high intensities

- At a rate of 10^{18} neutrinos using the EURISOL beta-beam facility:

Acccelerator Isotope	RCS $[10^{12}$ C]	PS $[10^{13}$ C]	SPS $[10^{13}$ C]	DR $[10^{14}$ C]	DR Peak Current [kA]
^{148}Dy	120	102	828	87.6	3.74
^{150}Dy	139	117	948	97.8	4.18
^{150}Ho	86.1	74.0	602	68.7	2.93
^{152}Tm	28.3	23.2	162	27.5	1.17
^{18}Ne	2.71	4.35	4.29	7.47	1.60

US studies



Machine	t_{ramp} (including injector chain) [s]	Γ_{max}(proton)	γ_{max} ($^6He^{2+}$)	γ_{max} ($^{18}Ne^{10+}$)
Tevatron	18	1045	349	581
RHIC	101 (41)	268	89	149
LHC	~1200	7600	2500	3500

- Tevatron most realistic scenario
  - Comparable fast acceleration in all energy regimes
  - γ_{top}=350
- About 70% survival probability for ^6He
  - Compare with 45% in the EURISOL DS (2 seconds accumulation time considered)
  - Reduced decay losses and activation during acceleration

Several studies on the physics reach exist, but annual neutrino rates have to be reviewed.

Site constraints

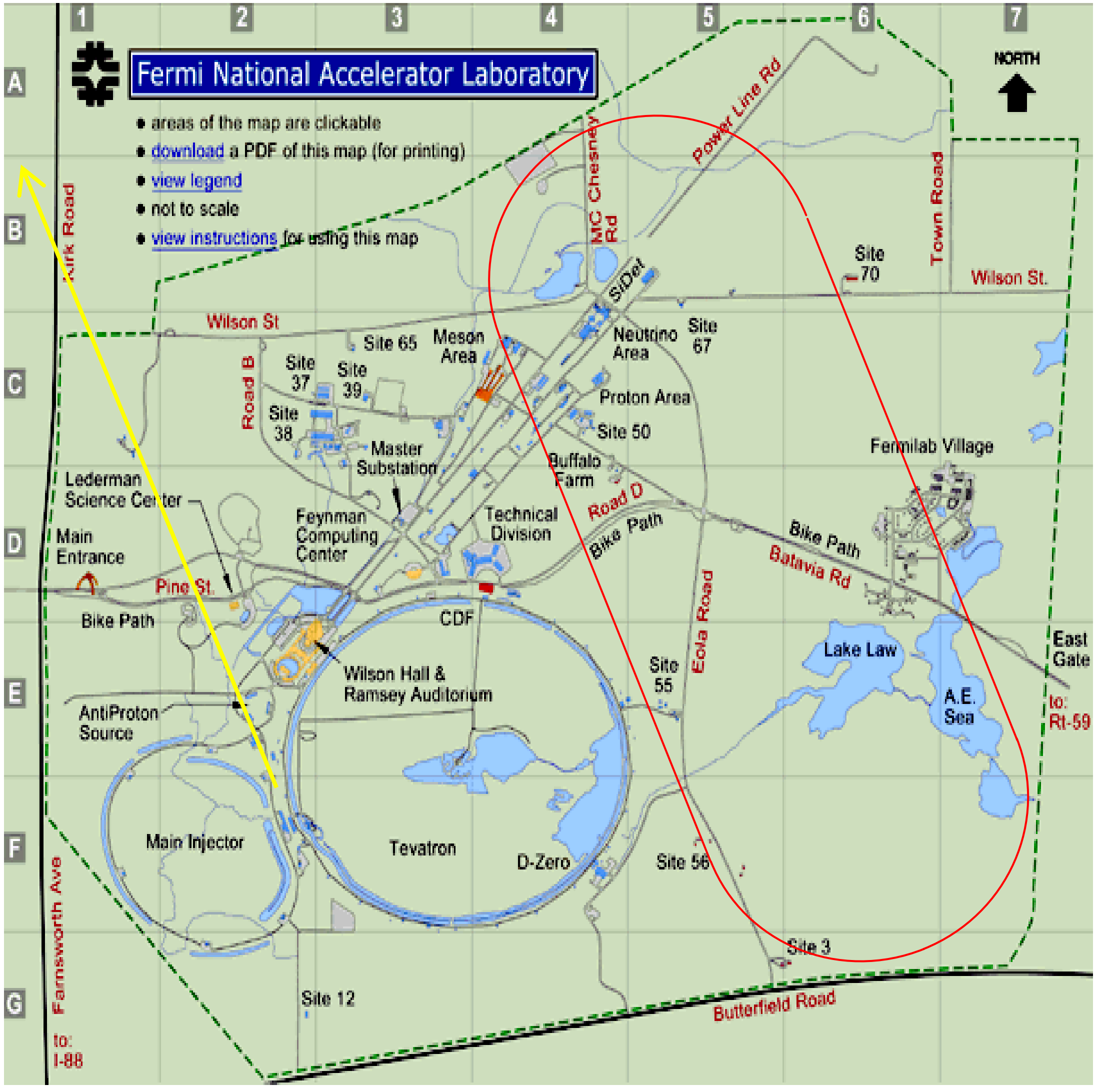
"Stretched Tevatron" aimed at Soudan

$B\rho$ = 3335 Tm
R = <u>1000 m</u> (75% 4.4T dipoles)
L_{SS}= ~3500

Total circumference:
approximately 2 x Tevatron

320m elevation @ 58 mrad

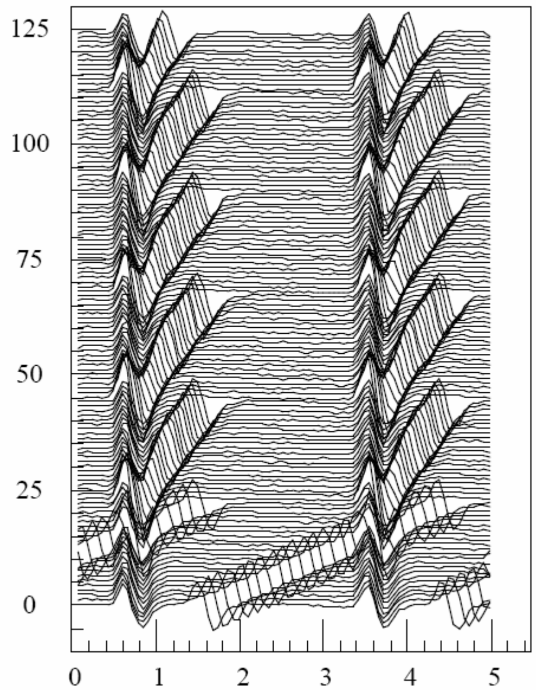
26% of decays in SS



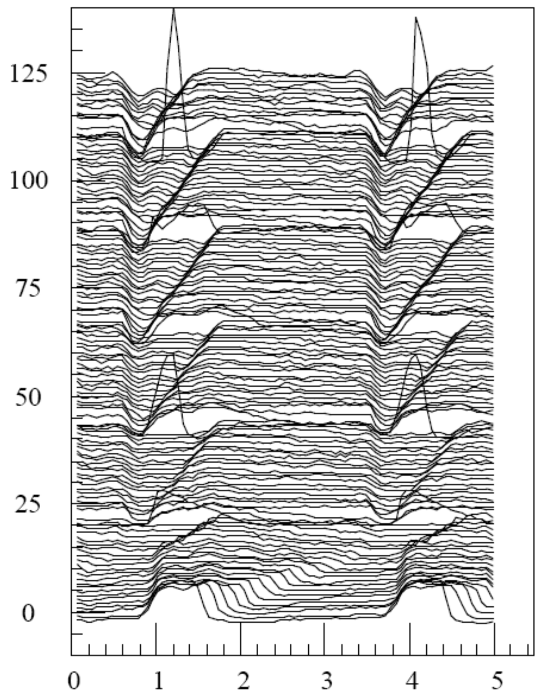
Accumulation with Barrier buckets (no duty cycle)

A Barrier Bucket Experiment for Accumulating
De-bunched Beam in the AGS[+]

M. Blaskiewicz, J.M. Brennan
AGS Dept. Brookhaven National Laboratory
Upton, NY 11973-5000 USA



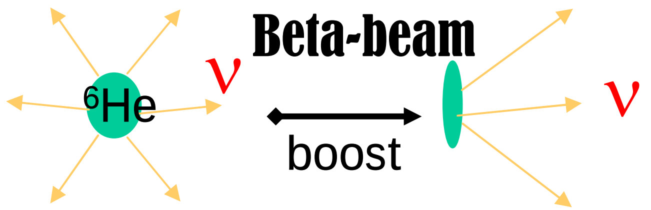
RF voltages (Barriers)



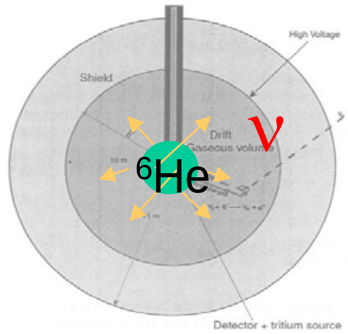
Beam current

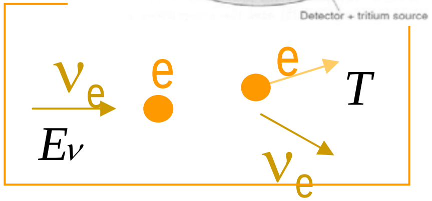
Low energy beta-beam

- The proposal
  - To exploit the beta-beam concept to produce intense and pure low-energy neutrino beams (C. Volpe, hep-ph/0303222, To appear in Journ. Phys. G. 30(2004)L1)
- Physics potential
  - Neutrino-nucleus interaction studies for particle, nuclear physics, astrophysics (nucleosynthesis)
  - Neutrino properties, like ν magnetic moment



$^{6}He \rightarrow {}^{6}Li + e + \bar{\nu}_e \quad Q_\beta = 4.\ MeV$





We have some questions to address

- Considering safety, cost and feasibility; can we agree on a set of baselines for the proposed future neutrino oscillation facilities?
- How do we compare the different facilities?
- Can we propose a road map for the future of this subject?

- **A High Intensity Neutrino Oscillation Facility in Europe**
  - CDR for the three main options: Neutrino Factory, Beta-beam and Super-beam
  - Focus on potential showstoppers
  - Preliminary costing to permit a fair comparison before the end of 2011 taking into account the latest results from running oscillation experiments
  - Total target for requested EU contribution: 4 Meuro
    - 3.5 MEuro from EU for SB, NF and BB WPs plus lab contributions
    - 1.5 MEuro to be shared between Mgt, Phys and Detectors WPs plus lab contributions
    - 4 year project
  - The IDS is an essential partner

Summary

- Beta-beam accelerator complex is a very high technical challenge due to high ion intensities
    - Activation
    - Space charge
  - So far it looks technically feasible.
- The physics reach for the EURISOL DS scenario is competitive for $\theta_{13}>1^{\circ}$.
  - Usefulness depends on the short/mid-term findings by other neutrino search facilities.
- The physics made possible with the new production concept proposed by Rubbia and Mori needs to be explored
- We need a study II
  - WP in Euroν Design study
  - Plenty of new ideas!
- You are warmly welcome to contribute!