Beta Beams,
EUROnu WP4

SEVENTH FRAMEWORK
PROGRAMME

ICE Section Meeting,
25/1/11

Production Ring for Beta Beams: status, news and plans

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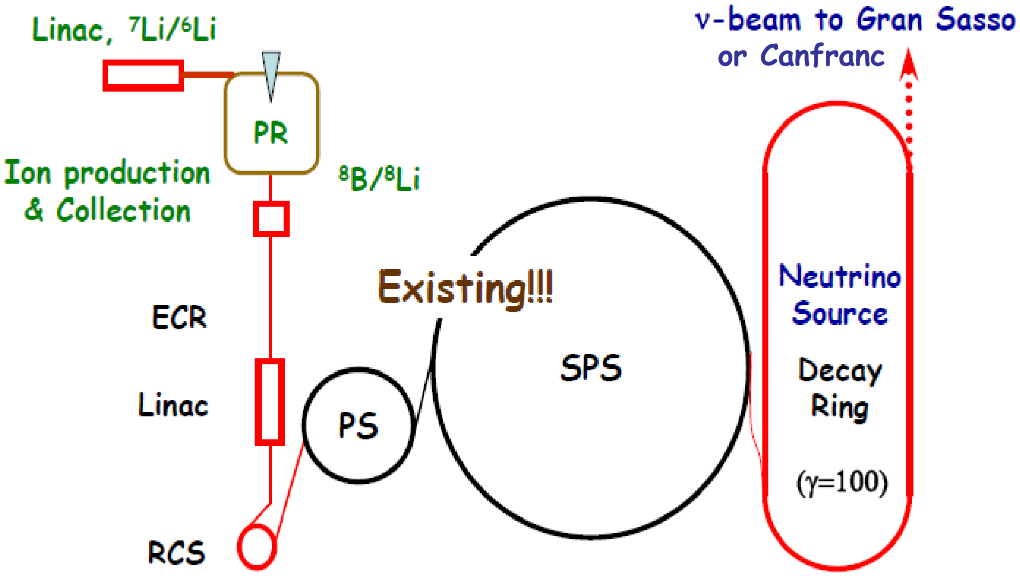
NTU-Athens & CERN

The Beta Beams

- Aim: **Production of e$^-$ (anti-) ν beam from β decay of radio-isotopes**



- ^{8}Li, ^{8}B ions
  - Originally introduced because lack of ^{18}Ne (maybe ok now)
  - Longer baseline for oscillation experiments → mass hierarchy
  - Studies started in 2009, within EUROnu
- High intensity
  - Implications for production, acceleration, storage
  - Assuming same losses and/or efficiencies as for ^{6}He,^{18}Ne (only ~few % reach Decay Ring) → Need 10^{14}/s of ^{8}Li, ^{8}B @ source

Production Ring

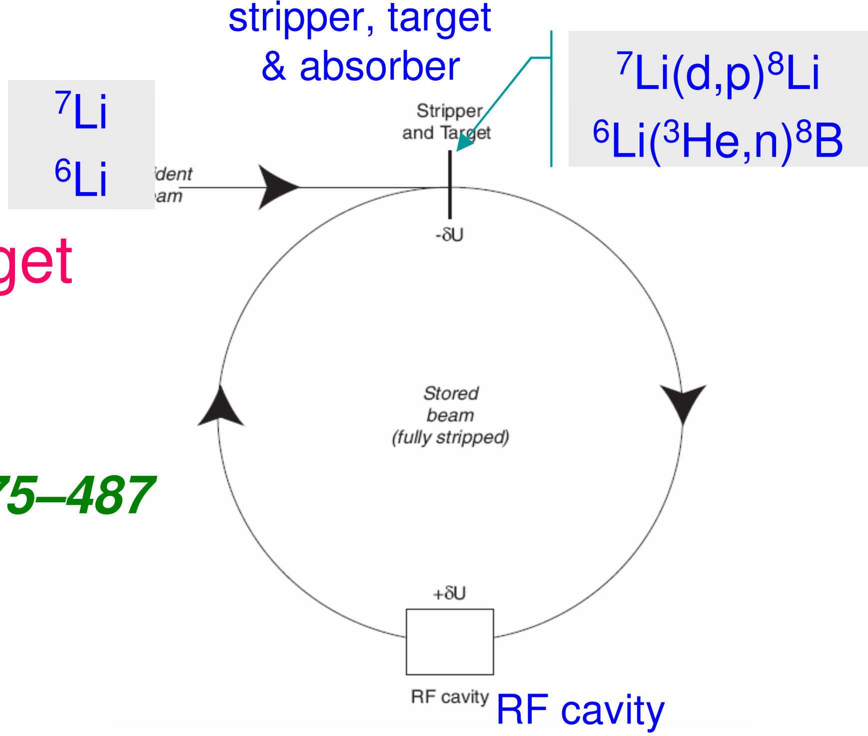
- Production ring
  - Multi-passage through internal target
  - Ionization cooling

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

See also:

→ ***D. Neuffer, NIM A 585 (2008) 109***

→ ***Y.Mori, NIM A 562 (2006) 591***



stripper, target & absorber

^{7}Li

^{6}Li

^{7}Li(d,p)^{8}Li

^{6}Li(^{3}He,n)^{8}B

RF cavity

- Compact ring: ~10m circumference
- Inverse kinematics:

  Li beam @ ~25MeV and D or ^{3}He supersonic gas-jet target
- “ISOL” collection device for the ^{8}Li, ^{8}B radioisotopes

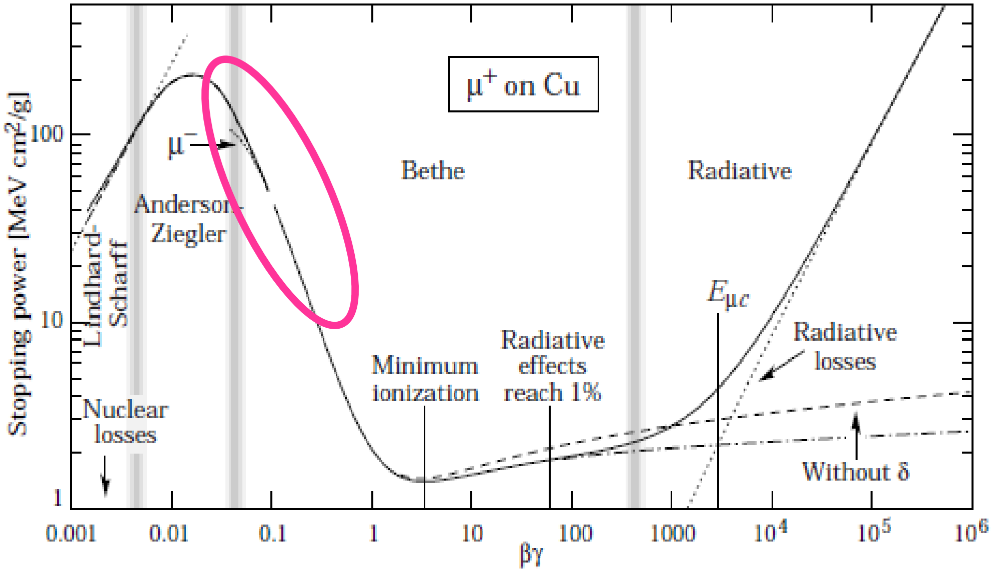
Ionization cooling

- Energy losses (dE/ds) in the target material (Bethe-Bloch)
- Only longitudinal component recovered in RF cavities

  → Transverse emittance shrinks

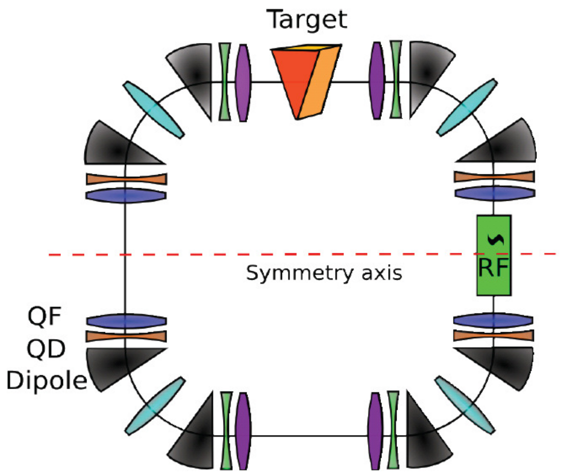
- Cooling in 6D
  - Heating in longitudinal
  - Need coupling between transverse and longitudinal:

    → Dispersion & wedge-shaped target



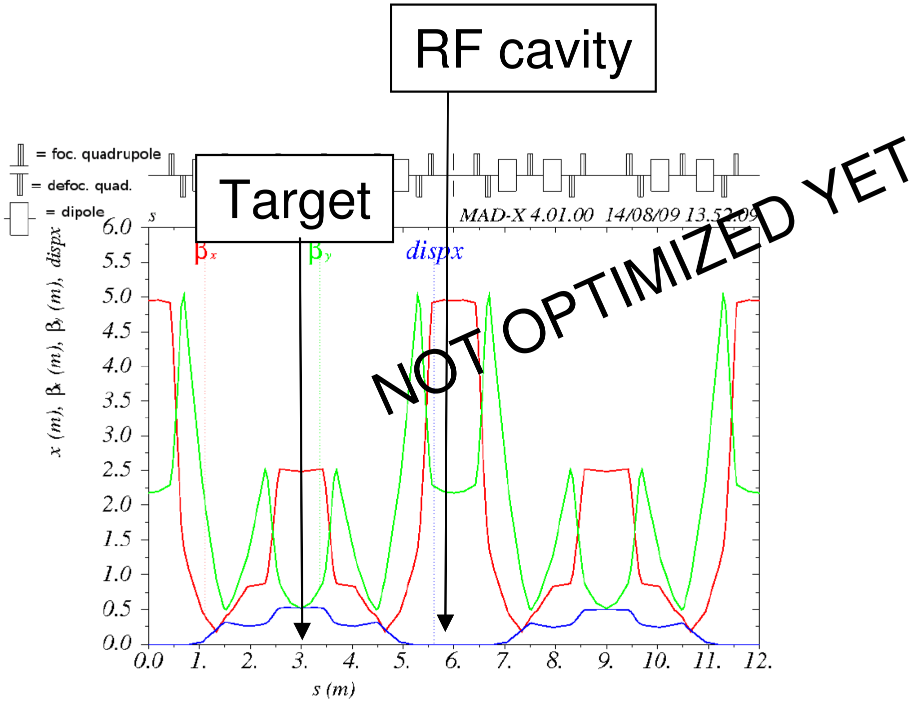
$$\sum J_i = 1 + 1 + \frac{\partial}{\partial E}\left(\frac{dE}{ds}\right)\Big|_{\Delta x=0} \begin{cases} 0.4 \quad \text{for } {}^6\text{Li} \\ 0.01 \quad \text{for } {}^7\text{Li} \end{cases}$$

Preliminary lattice



M. Schaumann, Aachen

Particle		^{7}Li
Energy	E_c	25 MeV
Relativistic gamma	γ_r	1.00383
Beam rigidity	$B\rho$	0.636 T m
Transition γ	γ_t	3.58
Tune	$Q_{x,y}$	2.58, 1.63
Natural chromaticity	$Q'_{x,y}$	$-3.67, -3.58$
β @ target	$\beta^*_{x,y}$	2.62 m, 0.35 m
Dispersion @ target	$D^*_{x,y}$	0.523 m, 0 m
Target thickness	t_0	0.27 mg/cm^2
	n_t	10^{19} atoms/cm^2
Energy losses @ target	E_{BB}	~ 0.30 MeV



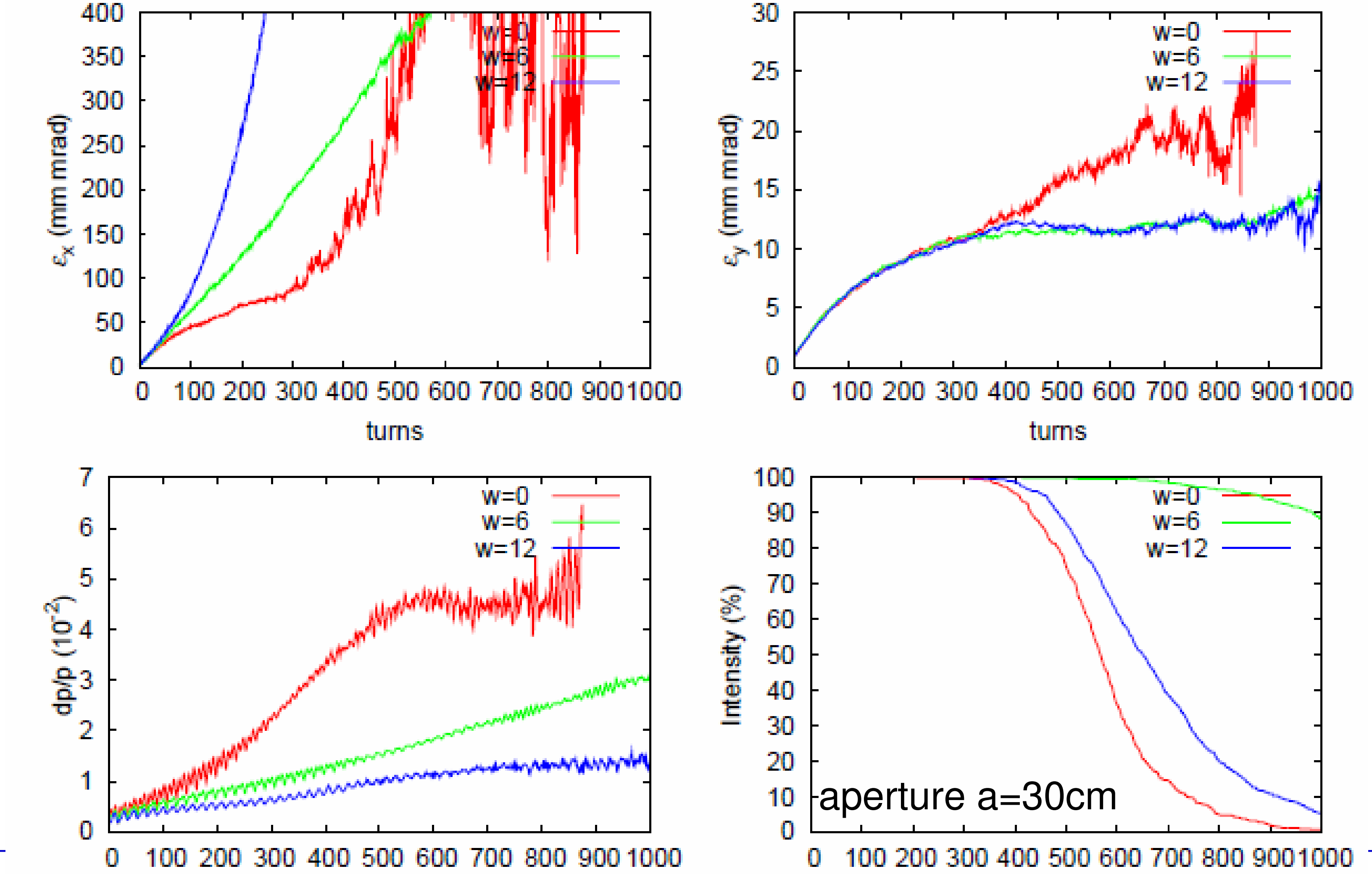
- C=12m
- Normal-conducting magnets
- Lattice → to be optimized
- Charge-exchange injection Li^{+1}
  → to be designed

6D tracking simulations

- SixTrack (collimation version)
- Target implemented as a special collimator element:
  - Analytical formulae for Multiple Coulomb Scattering and Energy Losses (benchmarked w. Geant4 simulations *(J.Wehner, Aachen)*)
  - Coupling w. MonteCarlo code FLUKA ongoing
    → *V.Vlauchoudis, D.Sinuela, E.B. (CERN)*
  - Rms emittances & Intensity evolution diagnostics
- SixTrack is for protons
  → need proton equivalent ring (same Bρ, same Δp/p recovered in RF)
- Benckmark w. MADX / PTC → OK!

6D tracking simulations

- Emittances H,V, dp/p and intensity evolution for different target wedge angles.



Technological issues & feasibility

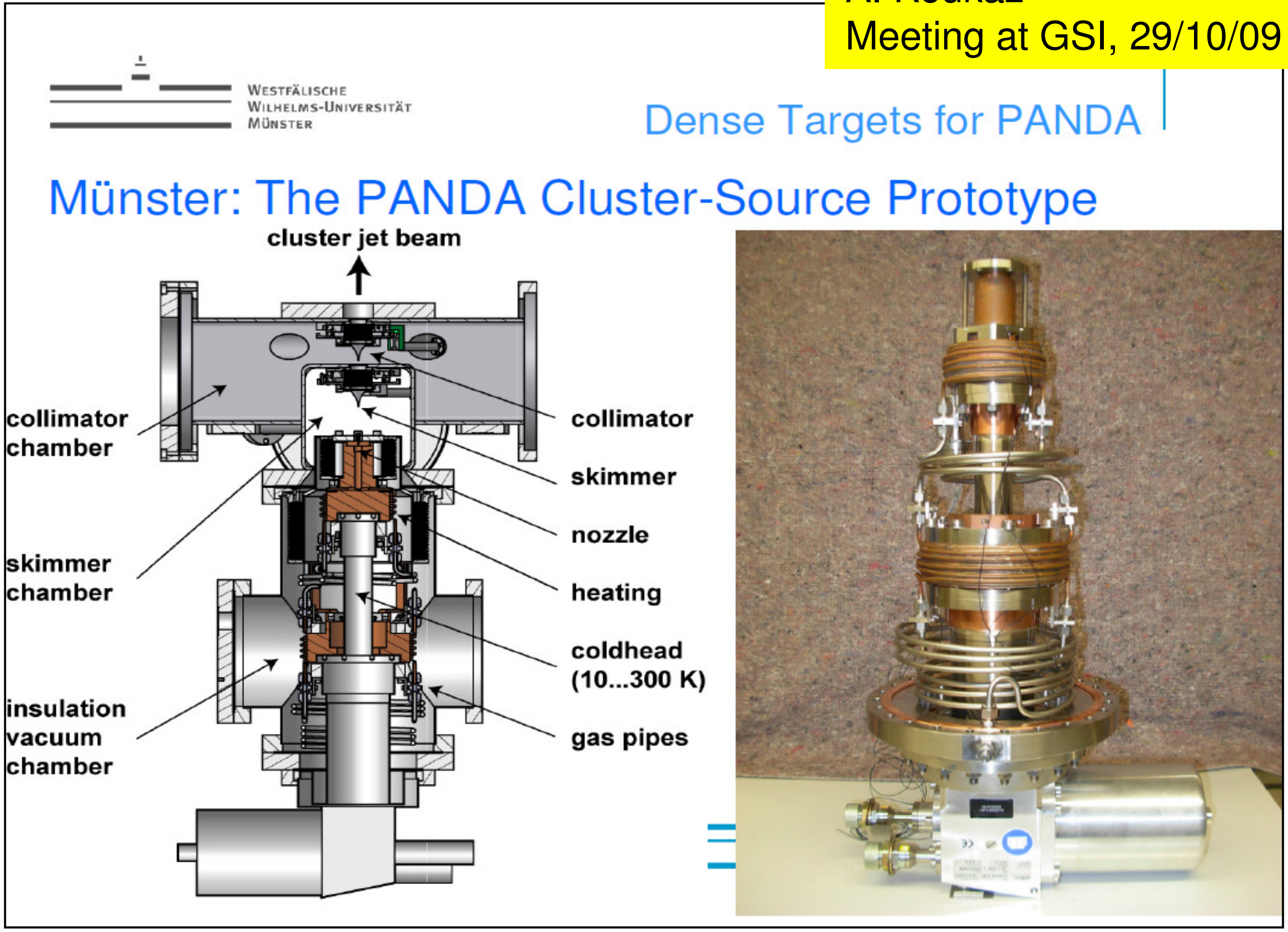
- High density gas-jet target (10^{19} atoms/cm^2 thick) in vacuum environment

A. Koukaz
Meeting at GSI, 29/10/09

Factor 10^4 larger !!!
then exisiting targets

Such gas-jet target densities would be OK in fusion or space applications,

BUT we need good vacuum for the RF cavity!



Westfälische
Wilhelms-Universität
Münster

Dense Targets for PANDA

Münster: The PANDA Cluster-Source Prototype

Lithium target

- Possible solution → go for a liquid target
  - (energy deposited ~300kW)
  - Better in direct kinematics: D or ^{3}He beam & Li target
- Investigate optimum projectile energy
  - Stopping power, target thickness, cross section, rev. frequency
- How to collect ^{8}Li/^{8}B?
  - angle (larger) & velocity (smaller) of produced ions

  → do we still need to stopping + diffusion/effusion?

  → or... (electrostatic) separator?
- Implications for the stored beam (i-cooling, lifetime,...)

Direct vs. inverse kinematics

INVERSE

- ☺ ^{8}Li/^{8}B emitted at $\theta \sim 10^{o}$ similar energy as projectile
- 😐 Supersonic jet target
- ☺ Efficient cooling removal
- ☹☹ Low densities
- 😐 Collection + diff./effusion

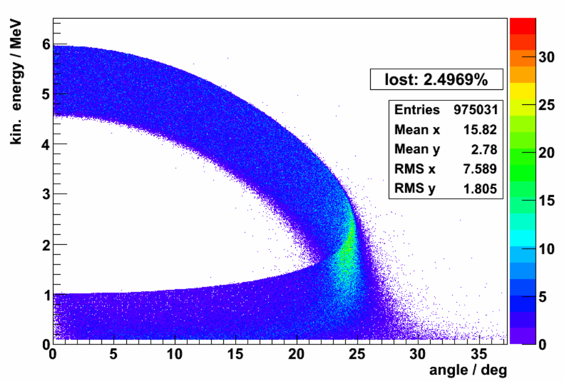
DIRECT

- 😐 30^{o} emission angle and smaller velocity
- ☹ Larger M.C. Scattering
- 😐 Larger emittance, less SC
- 😐 Solid/liquid target
- ☹ Cooling / jet instabilities
- ☺ High densities
- 😐 Collection? Spectrometer?

***See also D. Neuffer, NIM A* 585 (2008) 109**

Some (preliminary) studies

T. Weber (student from RTWH Aachen)



- Direct kinematics + solid/liquid target
  - → Factor 1000 gained
  - But still factor 10(100) missing
  - (assuming beam Nb=10^{12} ions)
  - The products
    - Will be emitted in a wide cone angle
    - And will exit the target (~10µm thick)
  - We may gain in higher energies (from 10 to 24 MeV)
    - Cross-section smaller, but...
    - Can use “thicker” target
    - Rev frequency increases more
    - BUT also energy straggling increases !!! TO BE CHECKED

Liquid Lithium target technology

- Energy deposited ~300kW, thickness ~10μm
- Liquid Lithium target technology for
  - Neutron production (but ~mm thick)
    - SARAF, LiLiT
    - IFMIF, irradiation facility for fusion materials
  - Heavy ion strippers

    → *see* ***Y. Momozaki, J. Nolen, C. Reed, V. Novick, J. Specht****. Development of a liquid lithium thin film for use as a heavy ion beam stripper.* ***Journal of Instr., 4(04):P04005, 2009.***

    - For U beam ~10-20MeV/n, ~few 10μm
    - Still R&D, they succesfully produced thin liquid films (Lithium and simulants), also looking at beam power deposition & instabilities
    - **Very promising!**

Next steps

- Direct kinematics feasibility:
  - Identify possible show-stoppers
  - Production rates
  - Realistic target thickness (and beam energy)
  - New collection device (or a separator, if feasible/preferred)
- Lattice optimization and injection design (in either direct/reverse)
- Beam-Target interaction w. Monte-Carlo codes:
  - Use correct physics inside tracking simulations (since we are at the limits of ionization cooling capabilities...)
  - Integration of FLUKA in SixTrack (with V. Vlachoudis, D. Sinuela)

Next steps

- Cross section measurements for $^{6}Li(^{3}He,n)^{8}B$
  - At INFN-Legnaro
  - Proposal submitted by V.Kravtchouk and E.Wildner
  - 3 weeks beam in April or May
- Prepare meeting w. Carlo Rubbia
- New collaborator for i-cooling simulations
  - Gianmaria Collazuol, researcher form Padova University
  - Meeting at CERN in February to define work plan

Look at other kind of rings

- FFAG-ERIT (Emittance Recovery Internal Target)
  - ***see Y.Mori, NIM A 562 (2006) 591; K.Okabe et al, IPAC10, EPAC08,…***
  - Proton FFAG with internal Be target to produce neutron for BNCT
  - Zero Q’, large acceptance & no need of longitud. cooling
  - Visited KURRI lab. in Nov’10 + invited to FFAG’10 workshop
  - Investigation of possible experiment → in stand-by...
  - Simulations with code ICOOL to be adapted to our ions, but...
- Why not? Use existing CERN rings
  - e.g. AD, LEIR or ELENA(proposed), if available for us in >20 years…
  - Stochastic and/or electron cooling available
  - Reduce costings, have sinergies w. other CERN projects
  - Check production rates!!!

Conclusions

- The studies for the ^{8}Li and ^{8}B Production Ring as proposed by ***[C.Rubbia et al.]*** are studied within EUROnu
- A preliminary design is available.
- Optics studies done for the ^{7}Li(d,p)^{8}Li inverse kinematics, can be scaled to direct kinematics and B production
- The lattice requires tuning to maximize i-cooling efficiency (e.g. reduce beta at the target).
- 6D tracking tools (based on SixTrack) fully in place, predict what expected from i-cooling analytical estimations.
- The code SixTrack includes also the high order effects, e.g. chromaticity and second order dispersion, which are important.

Conclusions

- Progresses in the feasibility studies
- The thickness (10^{19}atoms/cm^2) required for gas-jet target in vacuum environment is a major issue.
  - Existing target reach 10^{15}atoms/cm^2
- The direct kinematics approach with a liquid Lithium target looks very promising
- R&D for thin liquid-lithium film used as heavy-ions strippers, we could probably profit from…
- Strong interest (reciprocal) from FFAG and mu-cooling communities
- Fruitful collaboration w. INFN Legnaro and Padova Univ.

Acknowledgments

...tried to list all people which helped me with material, ideas, answers, code support, but I'm sure I forgot many more:

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- G. Arduini, J. Barranco, C. Bracco, M. Chanel, P. Chiggiato, C. Hansen, R. Garoby, B. Holzer, M. Martini, V. Previtali, G. Prior, F. Schmidt, V. Vlauchoudis, E. Wildner (CERN),
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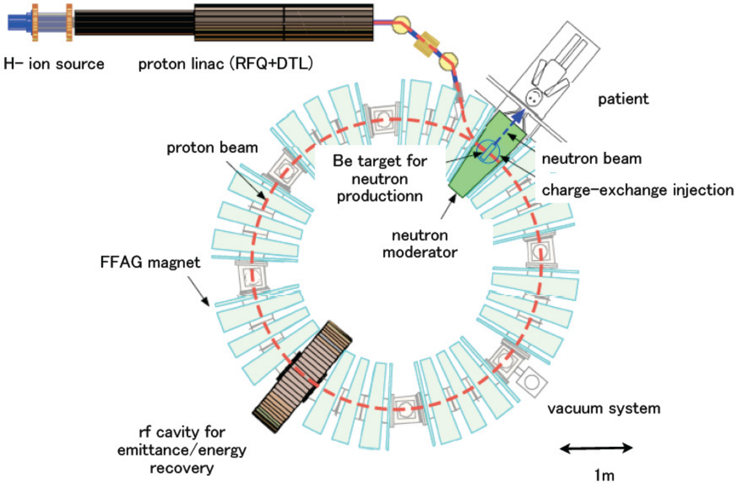
- O. Boine-Frankenheim (GSI), A. Koukaz (Munster U.)
- Y. Mori, K. Okabe (KURRI),
- S. Machida, M. Zisman, S. Berg,...(NuFact community)
- M. Cianausero, P. Mastinu, V. Kravchouk, (INFN, Legnaro)

Back-up slides

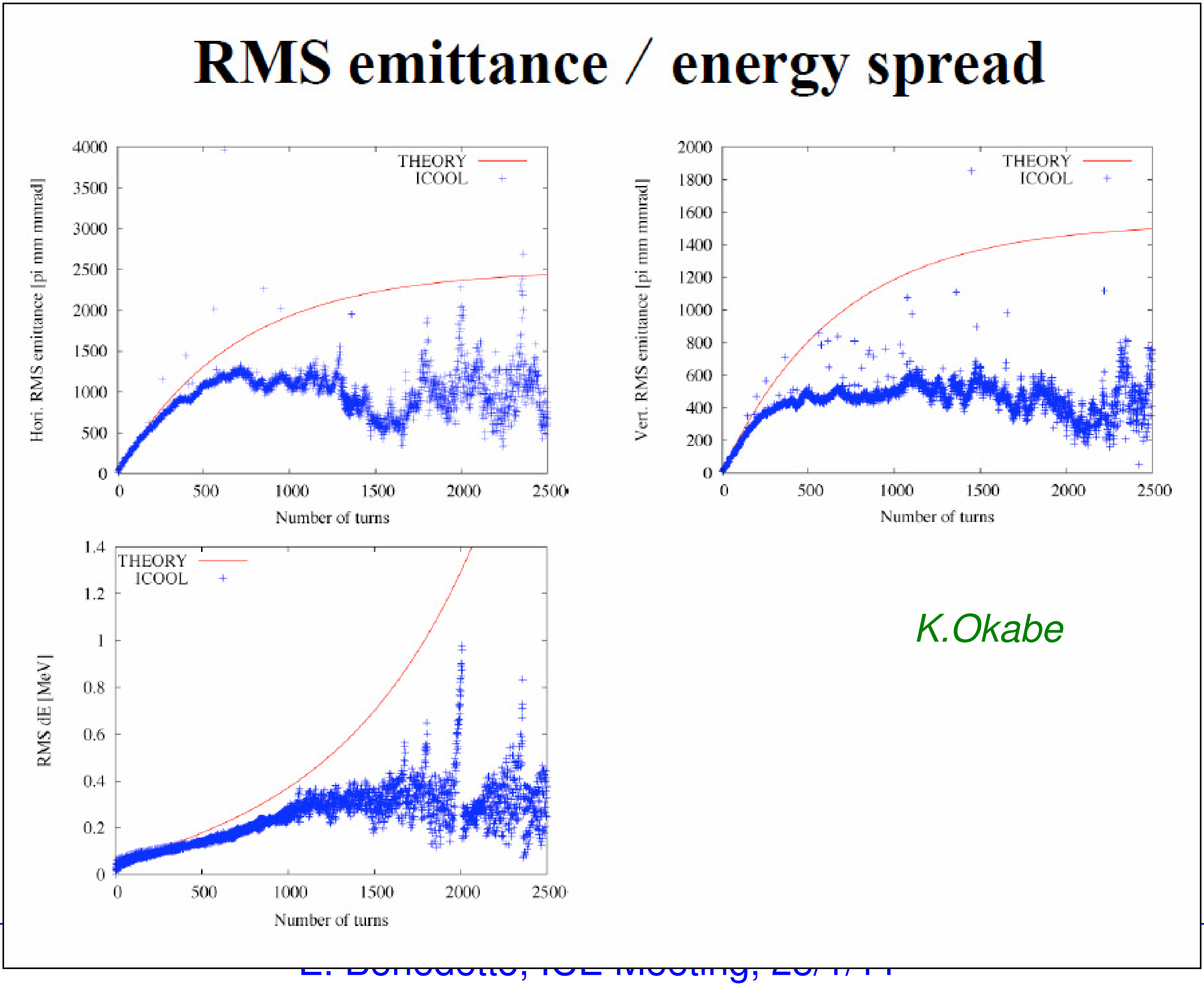
FFAG-ERIT @ KURRI (Osaka)

Schematic layout of FFAG-ERIT



K.Okabe et al, IPAC10, EPAC08,...

FFAG-ERIT @ KURRI (Osaka)



RMS emittance / energy spread

K.Okabe

What if I could use ERIT for my ions

	ERIT $p+{}^9Be \rightarrow n+{}^9B$	$d+{}^7Li \rightarrow p+{}^8Li$
Energy	11 MeV	5.5 MeV
Target	5μm ${}^9Be$	10 μm ${}^7Li$
ΔE_{RF}	43keV	104keV
$\tau=(dp/p)^{-1}$	510 turns	105 turns
ε (x10^{-6}) (full)	3388 / 1968	1115 / 648
σ (cm) (full, with dp/p=5%)	8.3 / 5.1	5.8 / 2.9
Jz	-1.41	-1.17

- Same $B\rho$=0.48 Tm
- Looks feasible! (even better performance than actual configuration)

Cooling rates and equilibrium emittance (1)

$$\frac{d\varepsilon_N}{ds} = -\frac{1}{p}\frac{dp}{ds}\varepsilon + \frac{\beta\gamma\ \beta_\perp}{2}\frac{d\left\langle\theta_c^2\right\rangle}{ds}$$

$$\boxed{\tau \sim \left(\int \frac{1}{p}\frac{dp}{ds}ds\right)^{-1} \approx 169 turns}$$

Damping time

$$\boxed{\varepsilon_\perp = \frac{1}{\beta\gamma}\frac{\beta\gamma\ \beta_\perp\left\langle\theta_c^2\right\rangle}{\int \frac{1}{p}\frac{dp}{ds}ds}}$$

Equilibrium emittances

$$\begin{cases} \varepsilon_x \sim 90\ \mu\text{m} \\ \varepsilon_y \sim 11\ \mu\text{m} \end{cases}$$

Cooling rates and equilibrium emittance (2)

$$\frac{d\sigma_E^2}{ds} = -2\underbrace{\frac{\partial}{\partial E}\left(\frac{dE}{ds}\right)\sigma_E^2}_{<0\ \to\ \text{blow-up}} + \frac{d\Delta E_{str}^2}{ds}$$

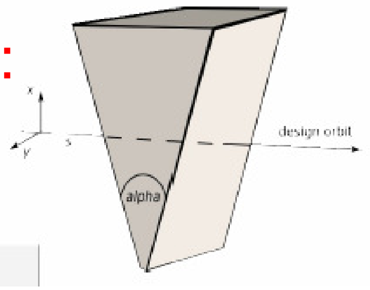
straggling

$$\boxed{\frac{d\varepsilon_z}{ds} = -\frac{J_z}{p}\frac{dp}{ds}\varepsilon + \dots}$$

$$\boxed{J_z = \frac{\partial}{\partial E}\left(\frac{dE}{ds}\right)\left(\frac{1}{p}\frac{dp}{s}\right)^{-1}}$$

<0 !!!!

If now we introduce Dispersion (and a triangular target shape):



$$\frac{\partial}{\partial E}\left(\frac{dE}{ds}\right) = \frac{\partial}{\partial E}\left(\frac{dE}{ds}\right)\Big|_{\Delta x=0} + \underbrace{\left(\frac{dE}{ds}\right)\frac{1}{\rho_0}\frac{d\rho}{dx}\frac{D}{\beta c p}}_{\text{at a different orbit } \Delta x = D\,\Delta p/p}$$

Cooling rates and equilibrium emittance (3)

If now we introduce Dispersion (and a triangular target shape):..

$$\boxed{J_z \to J_z + \frac{D}{\rho_0}\frac{d\rho}{dx}}$$

$$\boxed{J_x \to J_x - \frac{D}{\rho_0}\frac{d\rho}{dx}} \quad \boxed{J_y \to J_y}$$

can also introduce coupling x-y

Cooling can be transferred from transverse to longitudinal thanks to Dispersion + triangular target

Since sum of the three partition number is always the same, is computed for D_x=0:

$$\sum J_i = 1 + 1 + \frac{\partial}{\partial E}\left(\frac{dE}{ds}\right)\Big|_{\Delta x=0} \begin{cases} 0.4 \quad \text{for } {}^6\text{Li} \\ 0.01 \quad \text{for } {}^7\text{Li} \end{cases}$$

Due to Bethe-Bloch shape, NO possibility to effectively cool → but only to keep a constant emittance or not to heat it "too much"

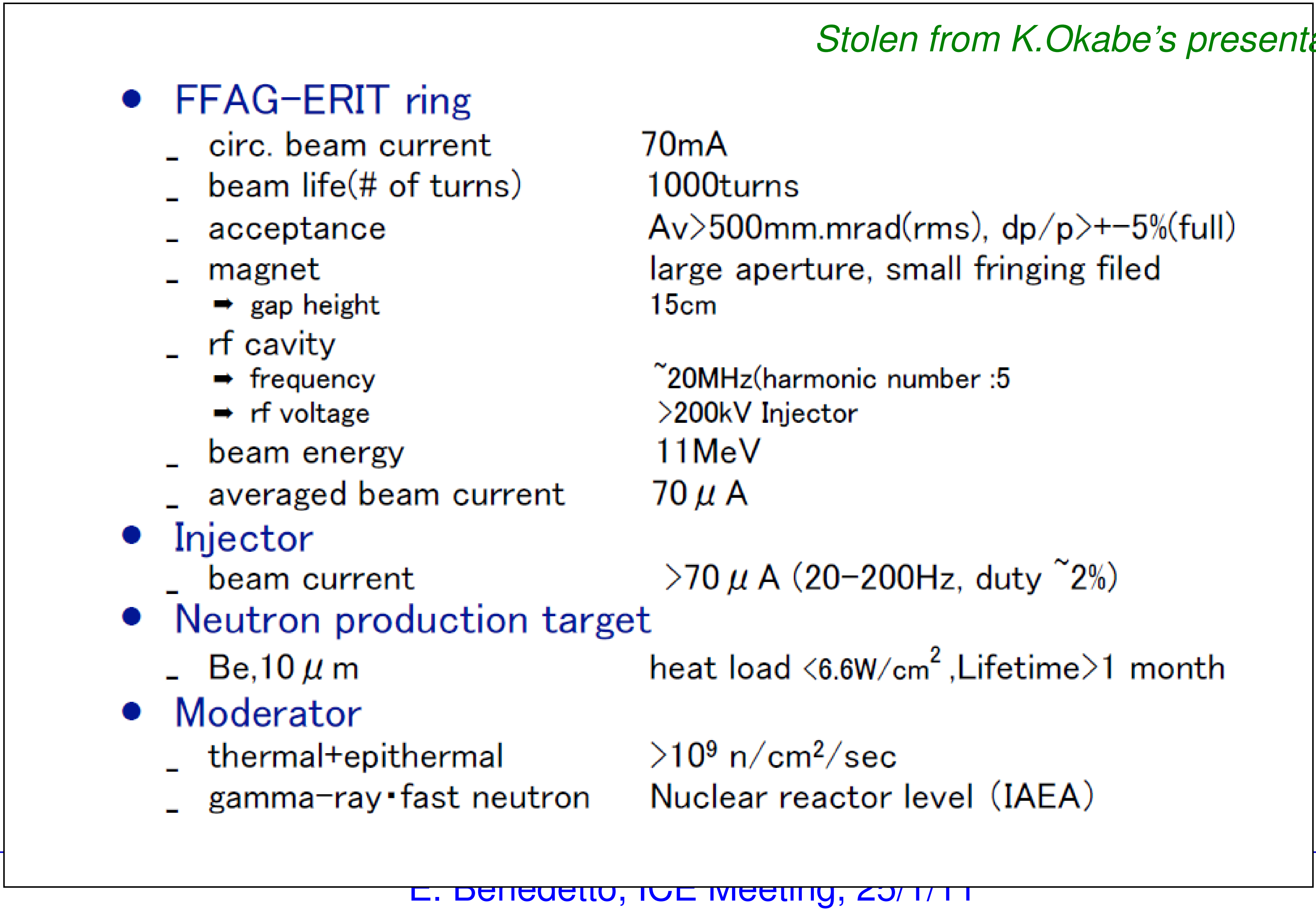
Production: requirements

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

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

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

What if I could use ERIT-FFAG for my ions



Stolen from K.Okabe's presentation

- FFAG-ERIT ring

circ. beam current	70mA
beam life(# of turns)	1000turns
acceptance	Av>500mm.mrad(rms), dp/p>+-5%(full)
magnet	large aperture, small fringing filed
➡ gap height	15cm
rf cavity	
➡ frequency	~20MHz(harmonic number :5
➡ rf voltage	>200kV Injector
beam energy	11MeV
averaged beam current	70 μ A

- Injector

beam current	>70 μ A (20-200Hz, duty ~2%)

- Neutron production target

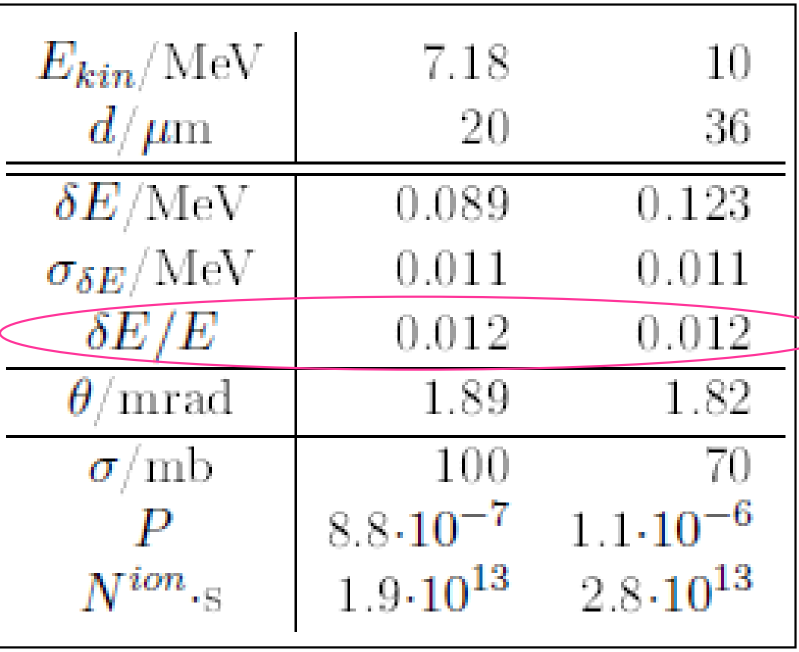
Be,10 μ m	heat load <6.6W/cm^2 ,Lifetime>1 month

- Moderator

thermal+epithermal	>10^9 n/cm^2/sec
gamma-ray・fast neutron	Nuclear reactor level (IAEA)

Direct kinematics, results

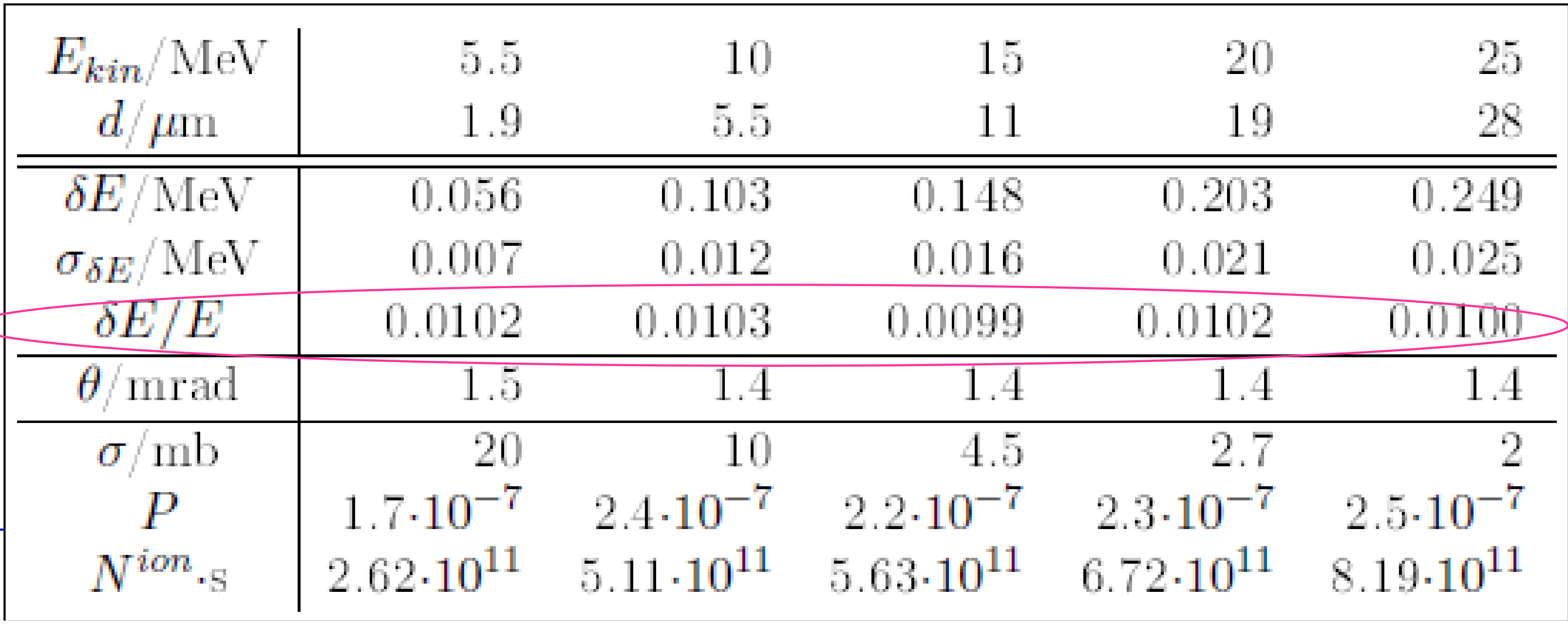
Torsten Weber



E_{kin}/MeV	7.18	10
$d/\mu\mathrm{m}$	20	36
$\delta E/\mathrm{MeV}$	0.089	0.123
$\sigma_{\delta E}/\mathrm{MeV}$	0.011	0.011
$\delta E/E$	0.012	0.012
θ/mrad	1.89	1.82
σ/mb	100	70
P	$8.8{\cdot}10^{-7}$	$1.1{\cdot}10^{-6}$
$N^{ion}{\cdot}\mathrm{s}$	$1.9{\cdot}10^{13}$	$2.8{\cdot}10^{13}$

← ^{8}Li production (D beam)

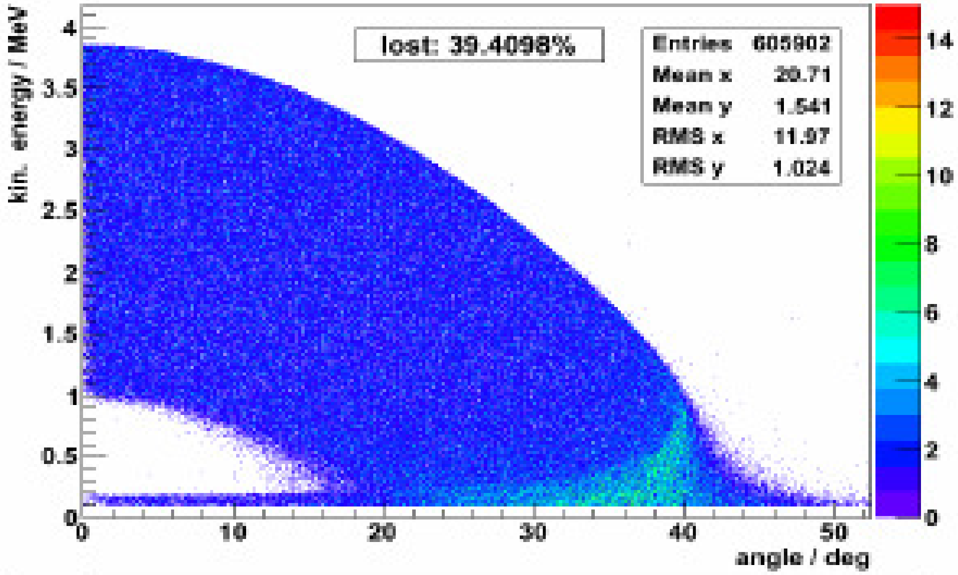
↓ ^{8}B production (^{3}He beam)

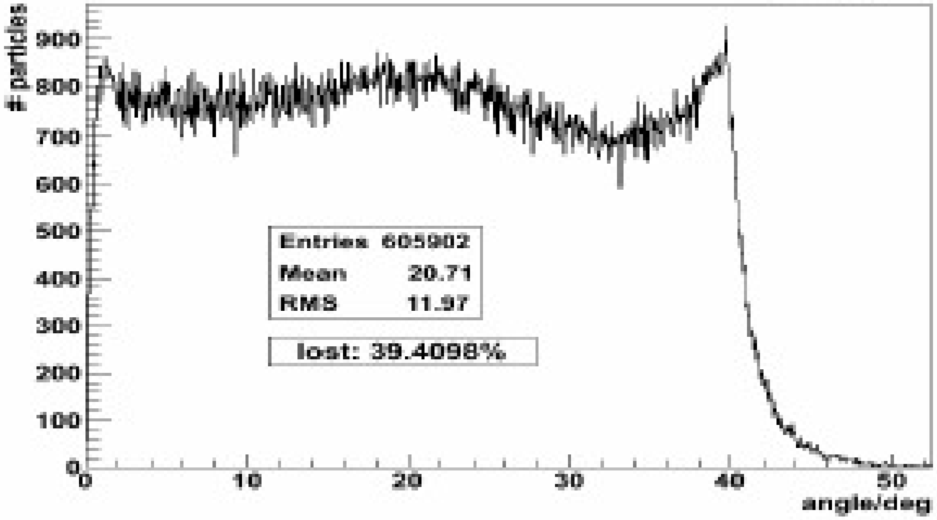


E_{kin}/MeV	5.5	10	15	20	25
$d/\mu\mathrm{m}$	1.9	5.5	11	19	28
$\delta E/\mathrm{MeV}$	0.056	0.103	0.148	0.203	0.249
$\sigma_{\delta E}/\mathrm{MeV}$	0.007	0.012	0.016	0.021	0.025
$\delta E/E$	0.0102	0.0103	0.0099	0.0102	0.0100
θ/mrad	1.5	1.4	1.4	1.4	1.4
σ/mb	20	10	4.5	2.7	2
P	$1.7{\cdot}10^{-7}$	$2.4{\cdot}10^{-7}$	$2.2{\cdot}10^{-7}$	$2.3{\cdot}10^{-7}$	$2.5{\cdot}10^{-7}$
$N^{ion}{\cdot}\mathrm{s}$	$2.62{\cdot}10^{11}$	$5.11{\cdot}10^{11}$	$5.63{\cdot}10^{11}$	$6.72{\cdot}10^{11}$	$8.19{\cdot}10^{11}$

Kinematics of the products
Lithium 8

Torsten Weber





Cut_E/MeV	Cut_φ/degree	N/%	$N^{ion}/10^{12}\cdot$s
0.5	5	41	7.79
0.5	10	34	6.46
0.5	15	27	5.13
0.5	20	20	3.80
0.5	25	14	2.66

(a) Results for 7.18 MeV kinetic energy of the deuterons and 20 μm target thickness. N_0^{ion} is $1.9 \cdot 10^{13}$/s.

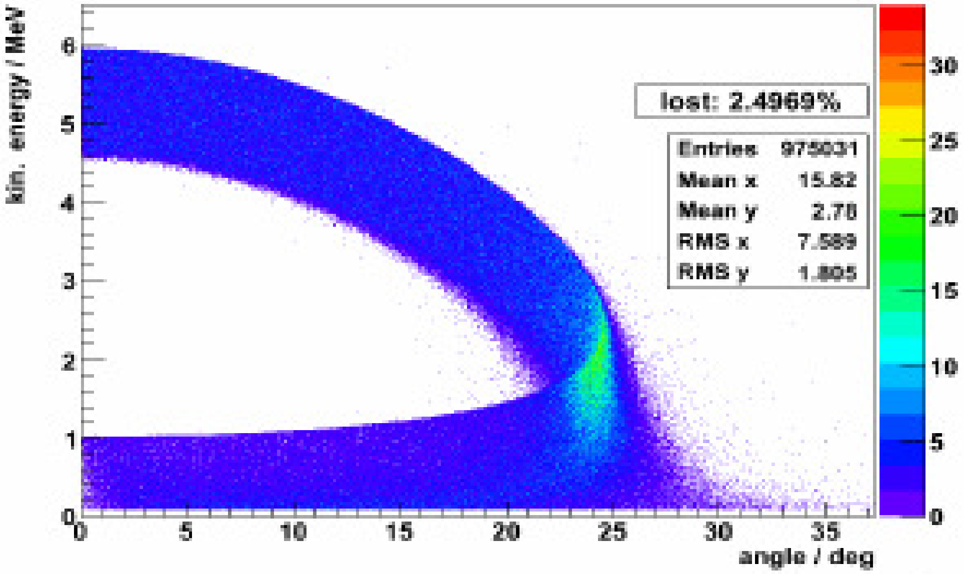
Cut_E/MeV	Cut_φ/degree	N/%	$N^{ion}/10^{12}\cdot$s
0.5	5	37	10.36
0.5	10	30	8.40
0.5	15	23	6.44
0.5	20	17	4.76
0.5	25	12	3.36

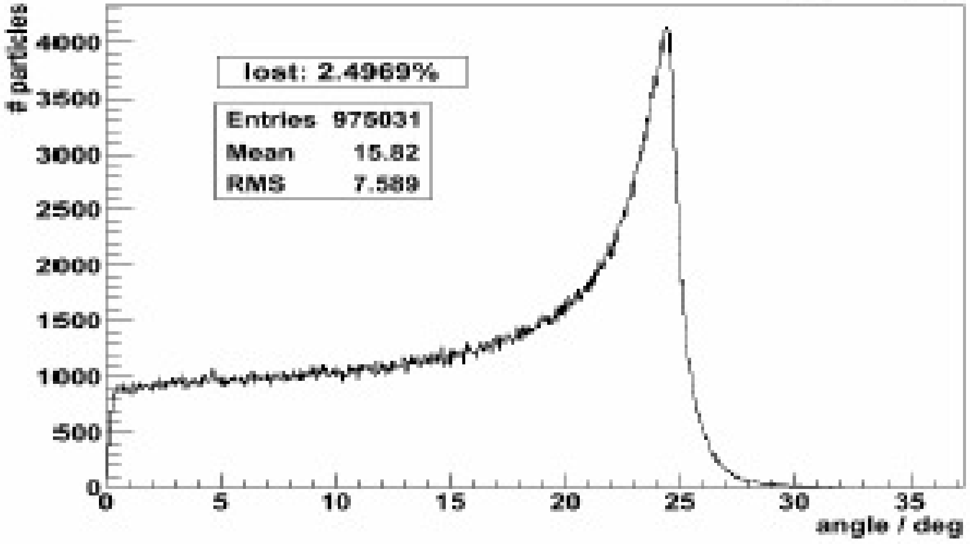
(b) Results for 10 MeV kinetic energy of the deuterons and 36 μm target thickness. N_0^{ion} is $2.8 \cdot 10^{13}$/s.

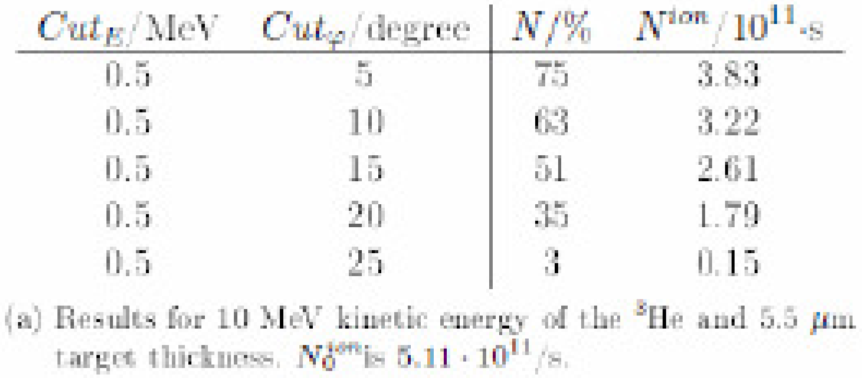
- 2-body kinematics
- Geant4 simulation of the products

Kinematics of the products
Boron 8

Torsten Weber

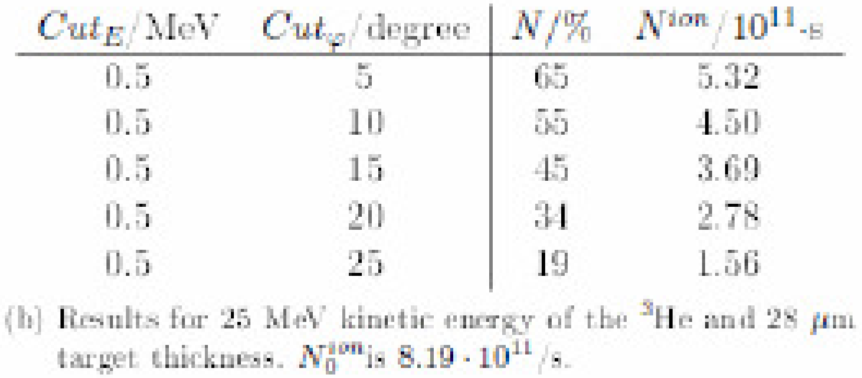






Cut_E/MeV	Cut_φ/degree	N/%	$N^{ion}/10^{11}\cdot s$
0.5	5	75	3.83
0.5	10	63	3.22
0.5	15	51	2.61
0.5	20	35	1.79
0.5	25	3	0.15

(a) Results for 10 MeV kinetic energy of the ^{3}He and 5.5 μm target thickness. $N_0^{ion}$is $5.11 \cdot 10^{11}$/s.



Cut_E/MeV	Cut_φ/degree	N/%	$N^{ion}/10^{11}\cdot s$
0.5	5	65	5.32
0.5	10	55	4.50
0.5	15	45	3.69
0.5	20	34	2.78
0.5	25	19	1.56

(b) Results for 25 MeV kinetic energy of the ^{3}He and 28 μm target thickness. $N_0^{ion}$is $8.19 \cdot 10^{11}$/s.