Drive Beam Long Transfer Line

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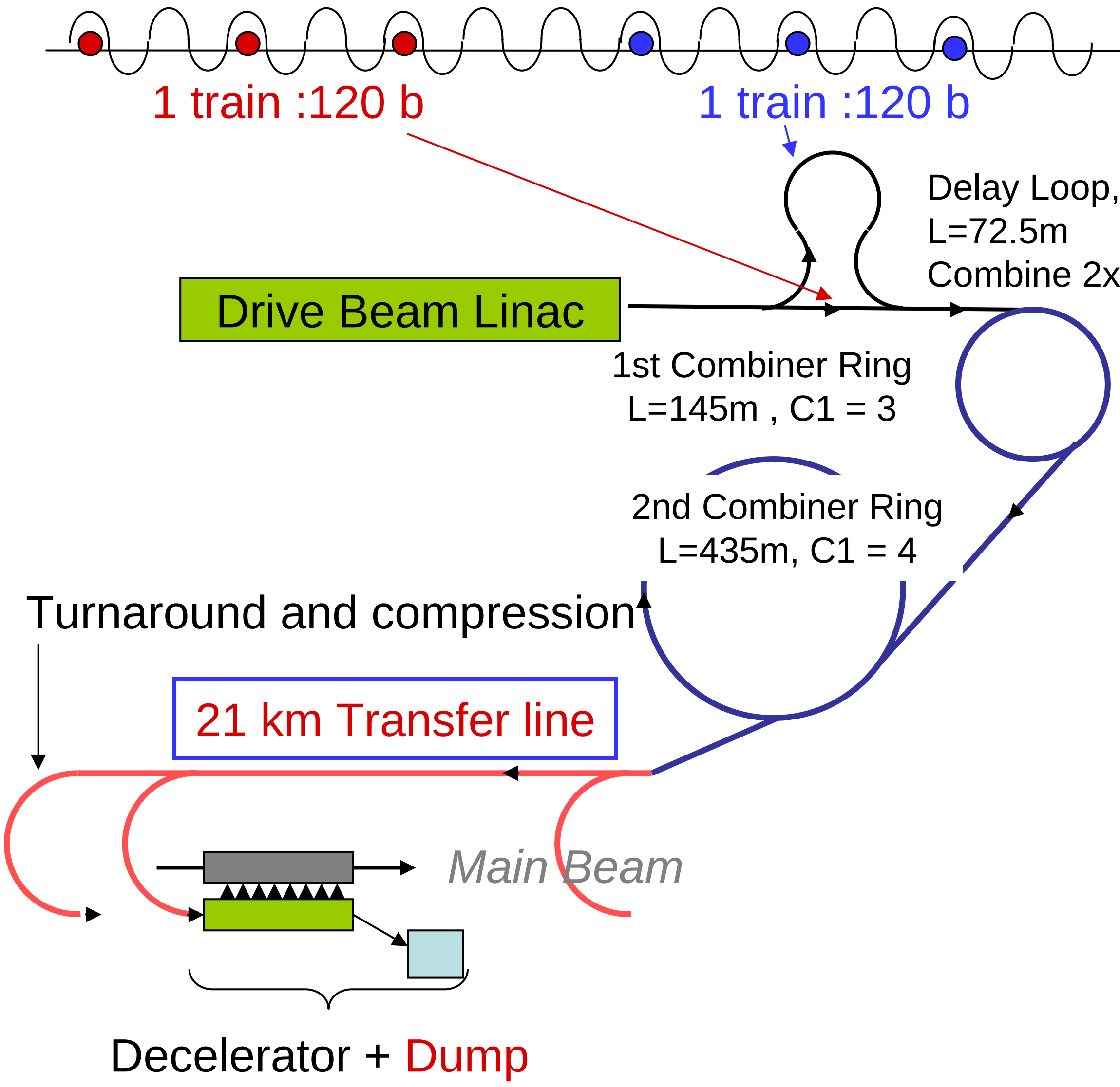
Outline

- DB complex schematic
- Long transfer line
- Turn-around and dump
- Combiner rings : Synchrotron Radiation
- Open issues
- Summary

Drive Beam schematic



1 train :120 b

1 train :120 b

Delay Loop,
L=72.5m
Combine 2x

Drive Beam Linac

1st Combiner Ring
L=145m , C1 = 3

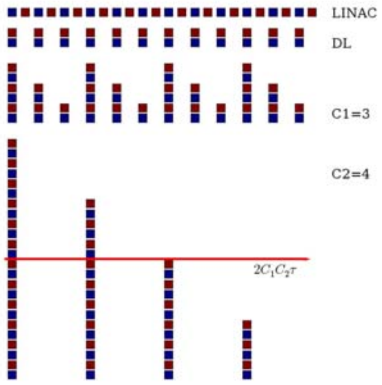
2nd Combiner Ring
L=435m, C1 = 4

Turnaround and compression

21 km Transfer line

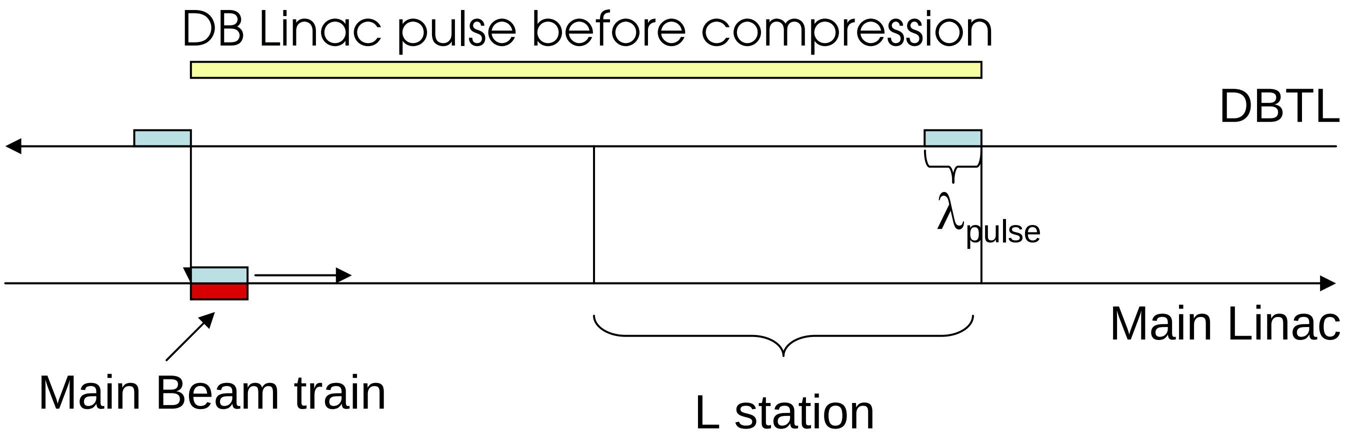
Main Beam

Decelerator + Dump



Linac frequency	1	GHz
Bunch frequency Linac	0.5	GHz
Bunch frequency TL	12	GHz
DB Energy	2.37	GeV
DB Current	**101**	A
Bunch population	$5.2\ 10^{10}$	-
Bunch separation	0.025	m
Train duration	**241**	ns
Train length	**72.3**	m
Bunches/train	2892	-
Electrons/Train	$1.5\ 10^{14}$	-
Nb. Sectors in TL	24	-
Repetition frequency	50	Hz

Drive Beam structure



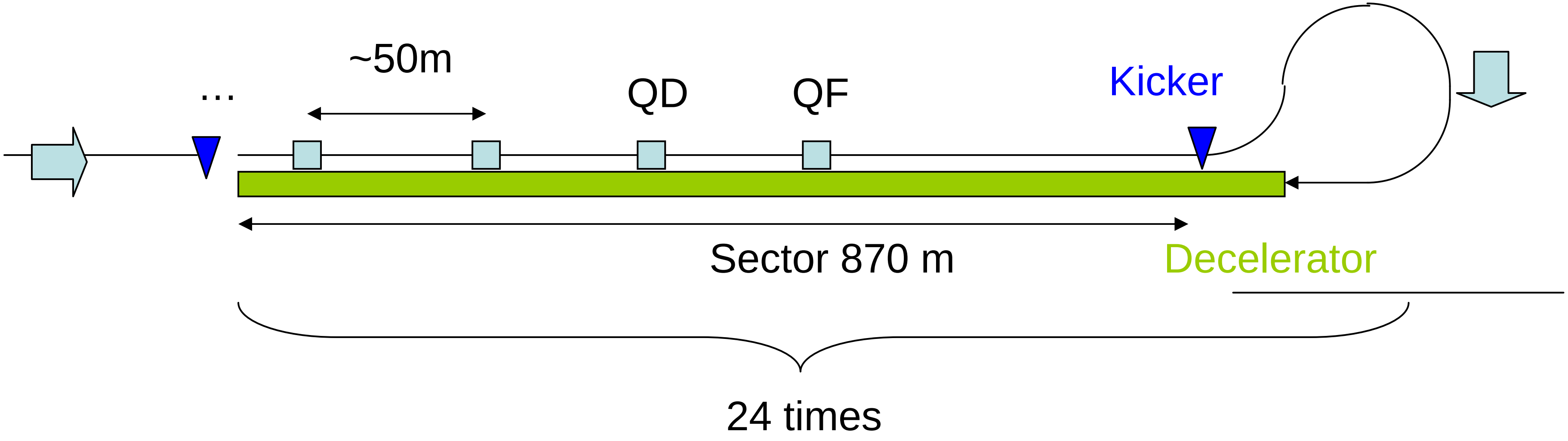
- A constant beam loading in the DB linac implies : $2L = 2C_1C_2\lambda$
- $\lambda = c\tau$ fixed by RF, presently : $\tau = 241.6$ ns , $\lambda = 72.5$ m
- → $L_{station} = 870$ m (+ 8 m for DB dump)
- Total pulse length in DBL : $\tau_{DBL} = 2N_{station}C_1C_2\tau = 1.39\text{e-}4$ s
- NOTE : each time τ is changed, $N_{station}$, C_1 , C_2 , drawings, etc must change as well → How many changes can we afford until 2010 ?

Long transfer line

- Straight 21km long line (twice)
- Optimise for performance and cost
- Specify vacuum requirements
- Specify vacuum chamber radius
- Specify magnet requirements

Long DB transfer line

- Aim : transport the Drive Beam trains from the central area of the site towards the head of the Main Linac
- Deflect a train in each turnaround, one after the other



FODO optimisation – use thin lens formalism

Ref. thin less formalism:
S.Y.Lee, Acc physics, p.54
E.Keil, in HAPE p.60

Number of cells $N = \frac{L_0}{\hat{\beta}} \frac{1+\sin\frac{\mu}{2}}{\sin\mu}$

Total magnet power (considering resistive wall)

$$A_p(\hat{\beta},\mu) = \frac{1}{\hat{\beta}^{5/3}} \frac{(1+\sin\frac{\mu}{2})^3}{\sin\mu\cos^2\frac{\mu}{2}}$$

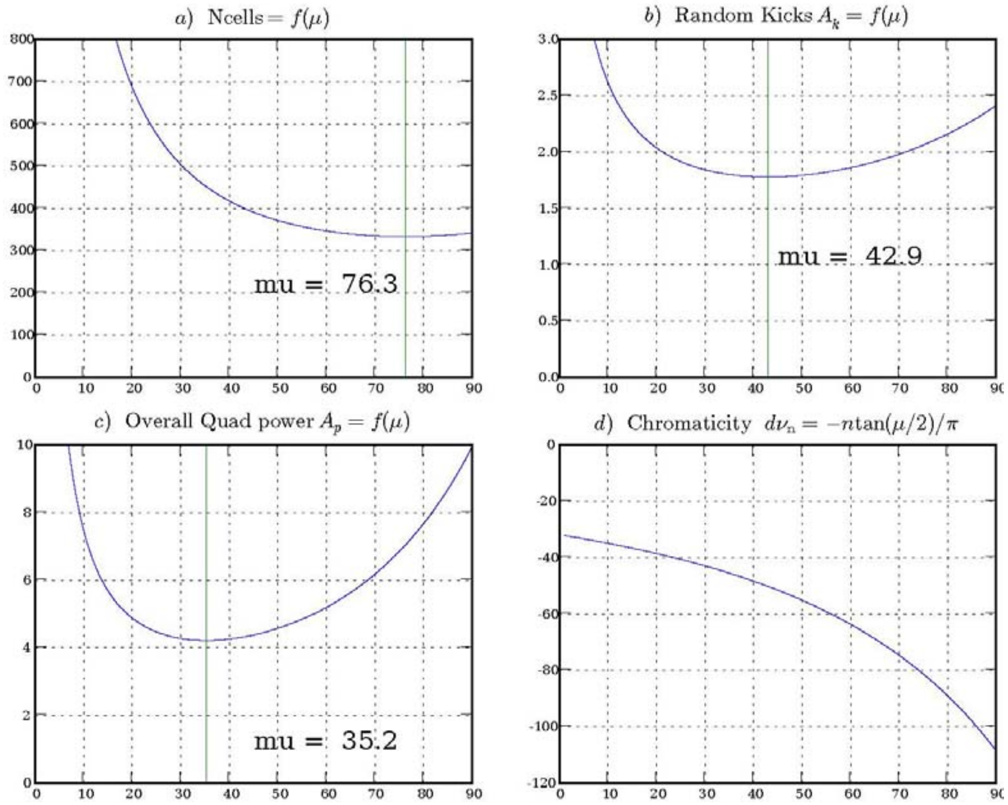
kick by random quadrupole displacement

$$\frac{\Delta_x}{\sigma_\beta} = \frac{1}{\hat{\beta}} \sqrt{\frac{L_0}{\epsilon}} \frac{2(1+\sin\frac{\mu}{2})}{\cos\frac{\mu}{2}\sin^{1/2}\mu} \times \delta_x$$

Chromaticity $C = -\frac{L_0}{\pi L}\tan\frac{\mu}{2} = -\frac{L_0}{2\pi\hat{\beta}} \frac{1+\sin\frac{\mu}{2}}{\cos^2\frac{\mu}{2}}$

These functions all factorise :

$$f(\hat{\beta},\mu) = g(\hat{\beta})\,h(\mu) \sim \frac{1}{\hat{\beta}^n}h(\mu)\ ,\ \text{with } n > 1\ .$$



Further calculations : with $\mu = 45^0$ and ε = 2e-8 m

β_{max} and $L_{\mathbf{cell}}$: as large as possible, except if collective effects exhibit an optimum β_{max} , see below

Chromatic effects

- Total phase advance : $\nu = 0.25$ Ncell = 26.5
- Detuning $\Delta\nu$ ($\delta p = 0.02, L=100$m) =~ 0.6 → +- 220 deg

- Kicks from random Quad misalignment
  - → Δ ($dx = 10^{-4}$ m , $L_0 = 21$ km) = 1.7 σ_β
  - Beam fully filamented
- Operability : better use a static solution, if possible at reasonable price

- Use chromatic correction, need
  - Sextupoles
  - A dispersion wave (D = 0.5-1.0 m) made with dipoles at the entrance of the line, to be closed after the entrance of every turnaround
- Still to be worked out (but see below for the sextupole strength)

Vacuum and ion issues

Ref.
Y.Baconnier, CERN PS 84-24
A.Poncet , CERN YR 99-05
T.Raubenheimer, SLAC Pub 5893

- The electron beam ionises the residual gas
- Electrons are repelled rapidly (light objects)
- Ions are attracted (or focused) by the beam and can be trapped inside (so called 'neutralisation' of the beam')

→ induces tune-shift & tune spread

Mean free path for electrons to produce a ion :

$$\lambda = \frac{1}{\rho_{\text{gas}}\sigma_{\text{ion}}}$$

$$\rho_{\text{lin,ion,train}} = \frac{p_{\text{Torr}} N_{\text{e,train}}}{\lambda_0}$$

$$\text{CO, pressure 1Torr} : \lambda_0 = 0.16 \text{ m}$$

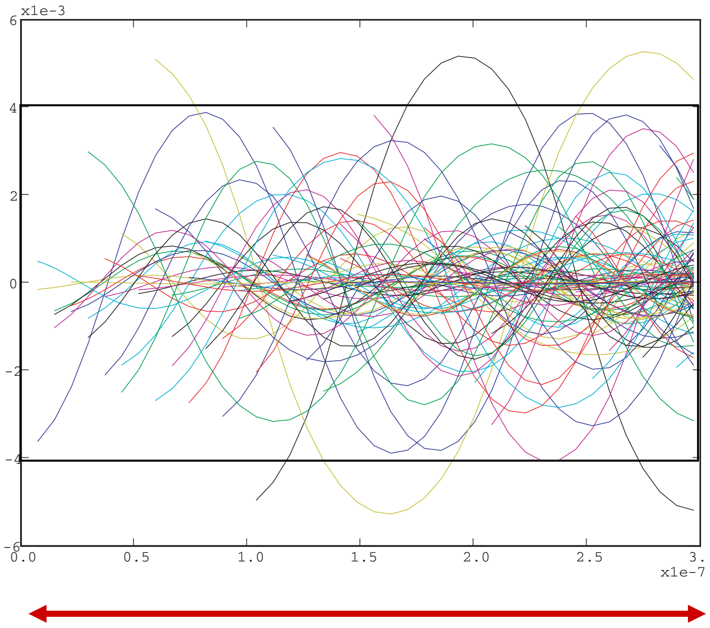
With 'standard' pressure (no getter, no bake-out)
One DB train , Ne = 1.5e14, $p=10^{-8}$ T : ρ_{lit} = 9.4e6 ion/m

Ion effects - I

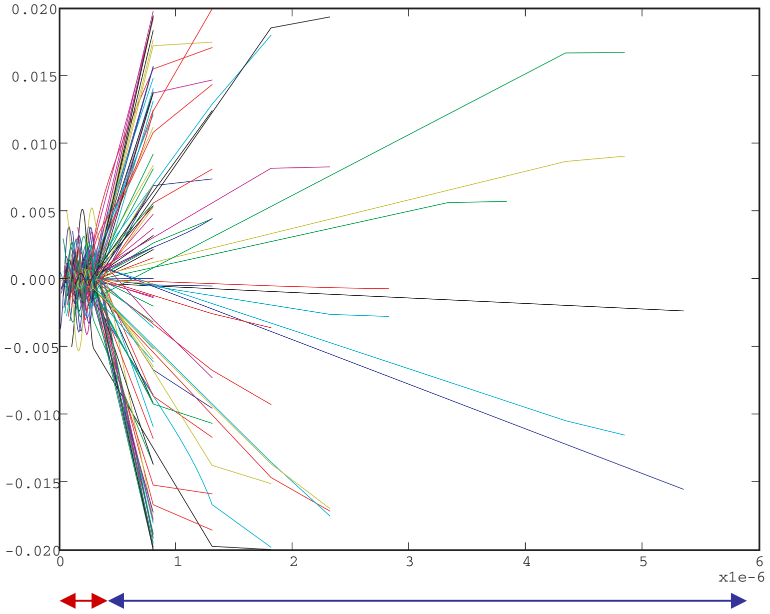
$$A_{\text{trap}} \geq \frac{N_{\text{e}} r_p \, \Delta L}{4\sigma_\beta^2}$$

A>10^{-4} trapped inside train
A< 10^5 untrapped between trains
CO : A=28

X [m]



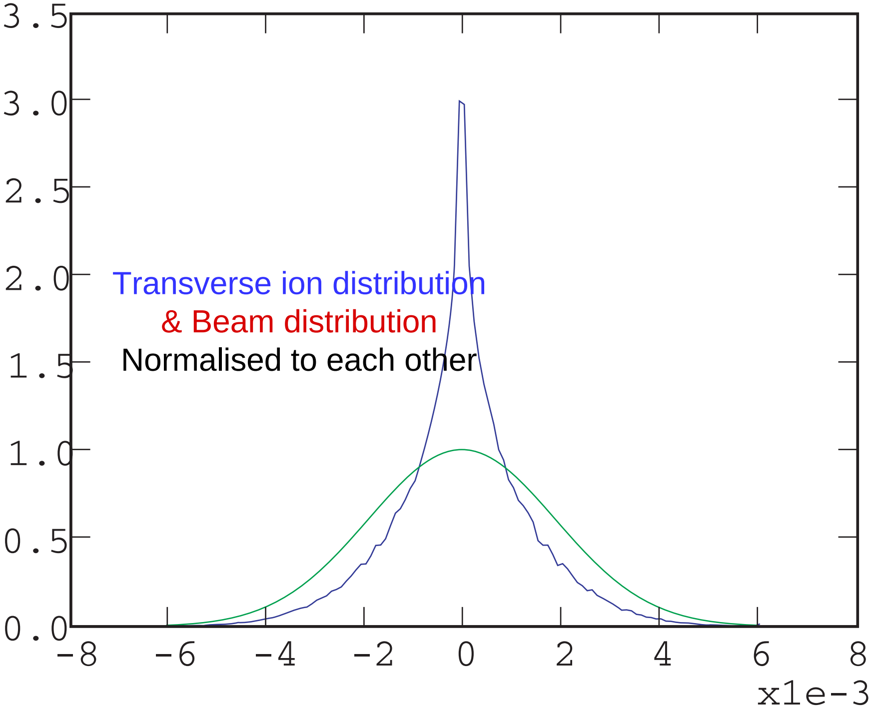
X [m]



Train length Time [s] Train Gap Time [s]

Ion effects - II

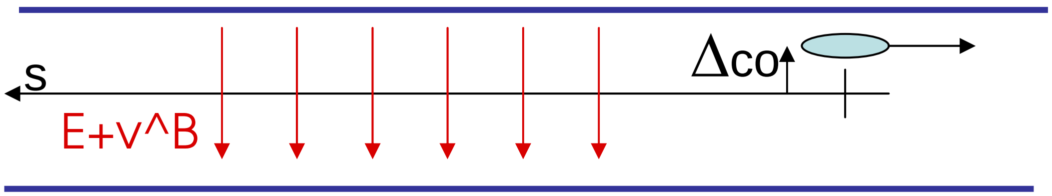
$$\Delta\nu = C\,\frac{\beta_\beta r_0 \rho_{\rm lit} L_{\rm ML}}{8\pi\gamma\sigma_\beta^2}$$



- C = 1 for equal beam & ion shapes
- Ratio at peak : C =~ 3
- $\Delta\nu$ =~ 0.45 at 10^{-8} Torr
  - Between head and trail of train
  - Between small and large (> σ_β) amplitude
  - → filamentation again
- If the trains ‘snake’
  - Ions and beam not always on the same orbit
  - → instabitilities on top

→ ‘standard’ 10^{-8} Torr not adequate
→ Need 10-100 times better (getter + bake-out) → $\Delta\nu < 0.01$

Collective effects - I



Thanks to key advice of S. Fartoukh

Ref: O.Henry and O.Napoly
Res. Wake potentials for short bunches, CLIC Note 142

- Worst case identified : resistive wake field induces transverse instability

$$\frac{dx'}{dz} = \frac{ne}{E}\frac{c}{\pi a^3}\sqrt{\frac{Z_0}{\pi\sigma}}\frac{1}{\sqrt{s}}\Delta_{\mathrm{x}} = W_{\perp}\frac{1}{\sqrt{s}}\Delta_{\mathrm{x}}$$

Δ_{x} : CO error + vac.ch. displacement of ahead bunches
dx'/dz : kick to a test particle at distance s behind

Total displacement of the last bunch :
- Sum over all bunches :

$$\frac{\delta x'}{dz} = W_{\perp}\Delta_{\mathrm{x}}\sum_{i=1}^{N} s_i^{-1/2} \simeq 2\sqrt{\frac{N-1}{s_b}}W_{\perp}\Delta_{\mathrm{x}}$$

-Quadratic sum over M half-period l_{hp} over L_0,
and convert to a normalised transverse displacement :

$$\Delta_n = \Delta_{\mathrm{x}}\sqrt{2M(N-1)}\, l_{\mathrm{hp}}\sqrt{\frac{\overline{\beta}}{\epsilon s_b}}W_{\perp}$$

DB transfer line with

L=100m, $\mu=\pi/4$, Δx=1mm rms

Normalised displacement (last bunch)

V.C. radius [m]	SS	Al	Cu
0.02	19.71	3.94	3.04
0.04	2.46	0.49	0.38
0.06	0.73	0.15	0.11
0.08	0.31	0.06	0.05
0.1	0.16	0.03	0.02

- Stainless steel ruled out

→ Al/Cu , radius R >= 60mm

dE/E loss over L_0 : 10^{-4}

Collective effects - II

- Simple model is optimistic (rigid train except for the last bunch)
- Test case compared with code of G.Rumolo
  - Same result if amplification of initial displacement is ~10%
  - Rapidly diverging beyond
- The vacuum chamber radius near R = 60 mm will be fined tuned once the optics is fixed (and cost optimised)

- Vacuum chamber (and magnet) dimensions will also be governed by this effect in the Combiner Rings
  - There lies a potential conflict with CSR which requires small vertical aperture

Collective effects - III

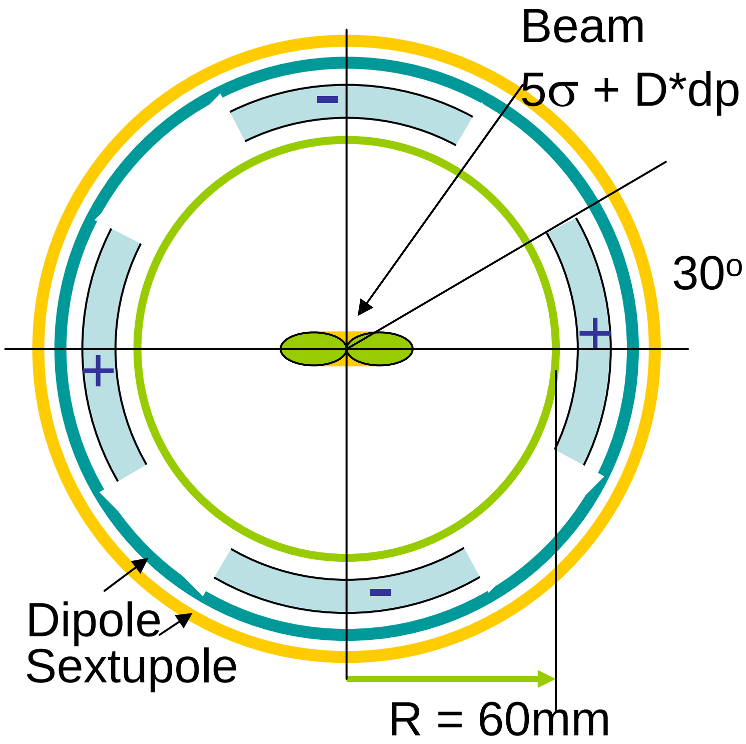
- Main Beam TL
  - E larger, bunches less populated and more spaced
    → better by a factor ~200
  - But vertical beam size ~ 200 times smaller

  → same conclusion for the radius of the vacuum chamber

- Damping rings : need check ?

- ILC damping rings : longer trains but larger bunch separation : large effect, feedback system foreseen (Wang, Bane, Raubenheimer, Ross EPAC 2006)

Magnets (with M.Bajko)



- Small power allows to consider cos(nθ) magnets, all in one yoke
  - Compact and light, adequate for installation at the ceiling of the tunnel
- (Option :
  - permanent magnet for ~90% of the Quad GL
  - powered trim-Q + S + B)

Linac length		21000	m	**COMBINED MAGNET**			
				Length	l	1	m
CELL				**Dipole**	**B**	**4.00E-03**	**Tm**
Length	L	100	m	**Quadrupole**	**B'**	**0.13**	**Tm/m**
Phase advance	mu	45	deg	**Sextupole**	**B''**	**1**	**Tm/m2**
Beam momentum	p	2.5	GeV/c	**Power (Quad)**			**W**
				Number of magnets	**n**	**840**	**(2 linac)**

Power, see below

Quadrupole data variations

Quad for drive beam of clic aperture radius 0.06 m

Parameter name	Symbole	Value					
Integrated gradient		0.13	0.131	0.132	0.128	0.133	Tm/m
Magnet length	L	1	1	1	1	1	m
Current density	j	5	4	3	2	1	A/mm2
Current	**I**	**39**	**44**	**58**	**72**	**40**	**A**
Total nr of turns	a	19	17	13	10	19	
Nr of layers	n_layer	1	1	1	1	2	
Winding width	hsec	3.3	3.8	4.6	6.2	6.5	mm
Wire dimension outside	ew	3.3	3.6	4.8	6.2	6.6	mm
Dissipated power in magnet	**Pmagnet**	**534**	**431**	**326**	**208**	**109**	**W**
Nominal voltage	Vmagnet	13.7	9.8	5.6	2.88	2.7	V
Nr. Of magnet /sector	nsector	16	16	16	16	16	
Total voltage of a sector	Vsector	**219.2**	**156.8**	**89.6**	**46.08**	**43.2**	V
Cooling channel radius	Rcool	1	1	1	1	1	mm
Pressure drop	DP	6	6	5.8	5.7	5.8	atm
Temperature rise	DT	36	27	18	10	7	K
Water flow	qm	0.213	0.229	0.26	0.3	0.21	l/min
Weigth of windings	Mmagnet	11.2	14	18	27	57	kg
Price of Copper wire	Price	324	409	550	787	1663	EUR

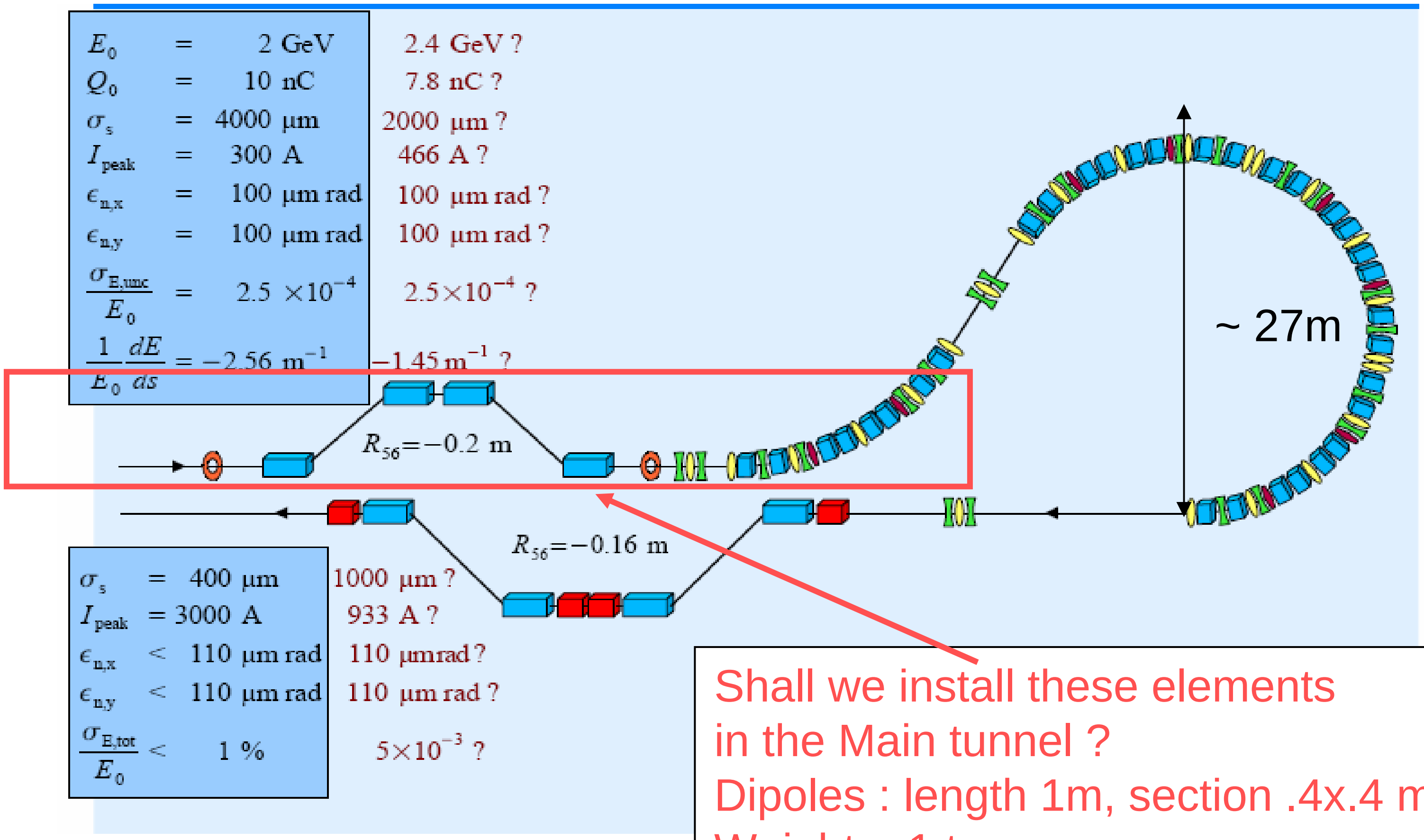
Price of electricity	0.022	0.022	0.022	0.022	0.022	EUR/kWh
Price of electricity for 1 magnet in 1 day	0.282	0.228	0.172	0.110	0.058	EUR
Difference of price	0	85	226	463	1254	EUR
Nr of days for justify the price difference	**0**	**374**	**1313**	**4216**	**21789**	**days**

Data M. Bajko

- Can make it with:
  - 300 W /mag. (Q+B+S)
  - Weight ~ 100kg
  - Comfortable electrical parameters
- Remains to be done
  - Integrate B+S
  - Detailed Field map study (and tracking with beam)
  - Optimise Ncell vs. vacuum chamber radius for cost (Pedro C.P. gave me prices for vac system)

Turn-around and Dump

Turnaround as of today , F. Stulle/PSI

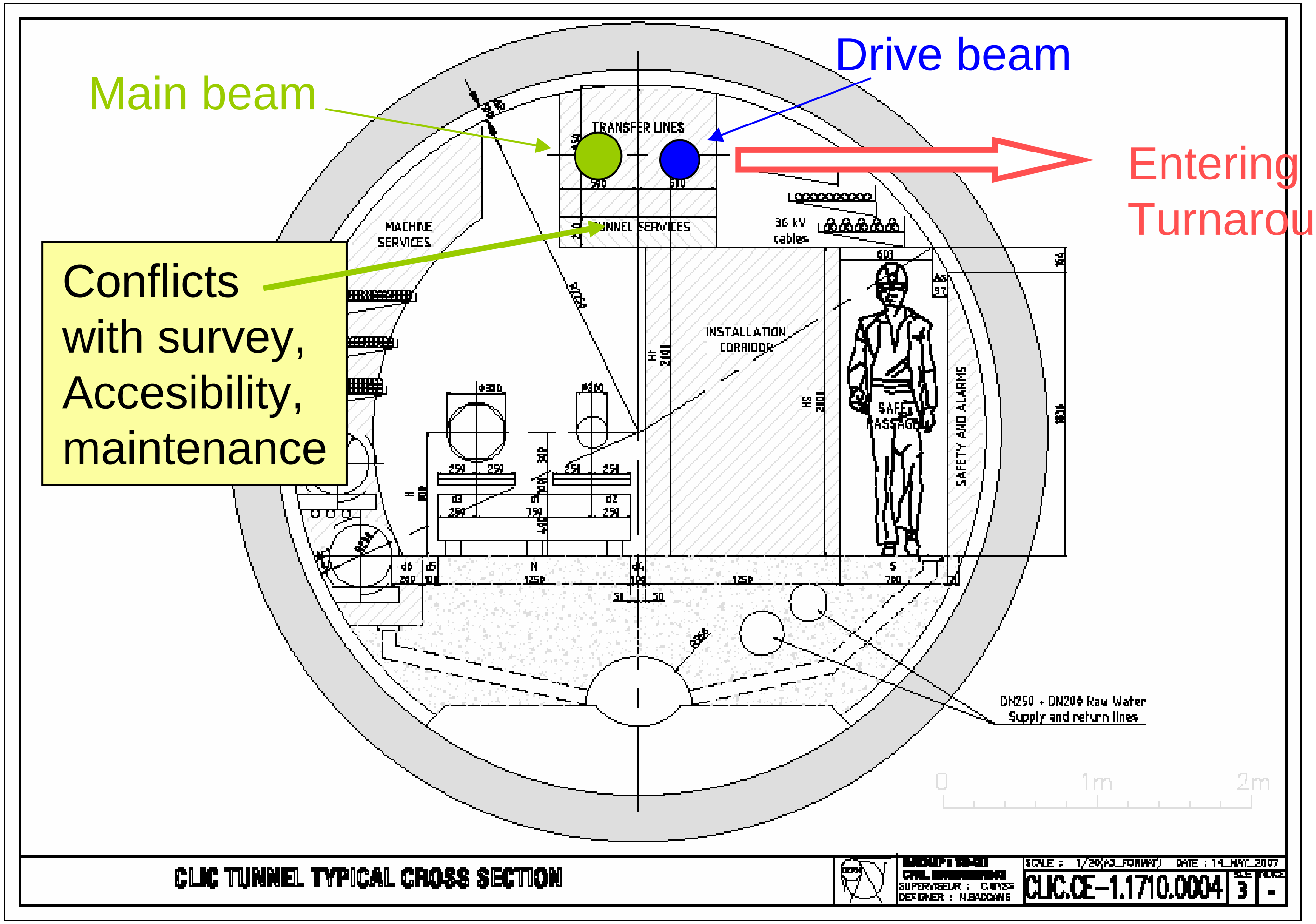


E_0	$= 2$ GeV	2.4 GeV ?
Q_0	$= 10$ nC	7.8 nC ?
σ_s	$= 4000$ µm	2000 µm ?
I_{peak}	$= 300$ A	466 A ?
$\epsilon_{\mathrm{n,x}}$	$= 100$ µm rad	100 µm rad ?
$\epsilon_{\mathrm{n,y}}$	$= 100$ µm rad	100 µm rad ?
$\frac{\sigma_{\mathrm{E,unc}}}{E_0}$	$= 2.5\times10^{-4}$	2.5×10^{-4} ?
$\frac{1}{E_0}\frac{dE}{ds}$	$= -2.56\ \mathrm{m}^{-1}$	$-1.45\ \mathrm{m}^{-1}$?

σ_s	$= 400$ µm	1000 µm ?
I_{peak}	$= 3000$ A	933 A ?
$\epsilon_{\mathrm{n,x}}$	< 110 µm rad	110 µmrad ?
$\epsilon_{\mathrm{n,y}}$	< 110 µm rad	110 µm rad ?
$\frac{\sigma_{\mathrm{E,tot}}}{E_0}$	< 1 %	5×10^{-3} ?

Shall we install these elements
in the Main tunnel ?
Dipoles : length 1m, section .4x.4 m^2
Weight ~ 1 ton

Main tunnel cross-section



Main beam

Drive beam

Entering Turnaround

Conflicts with survey, Accesibility, maintenance

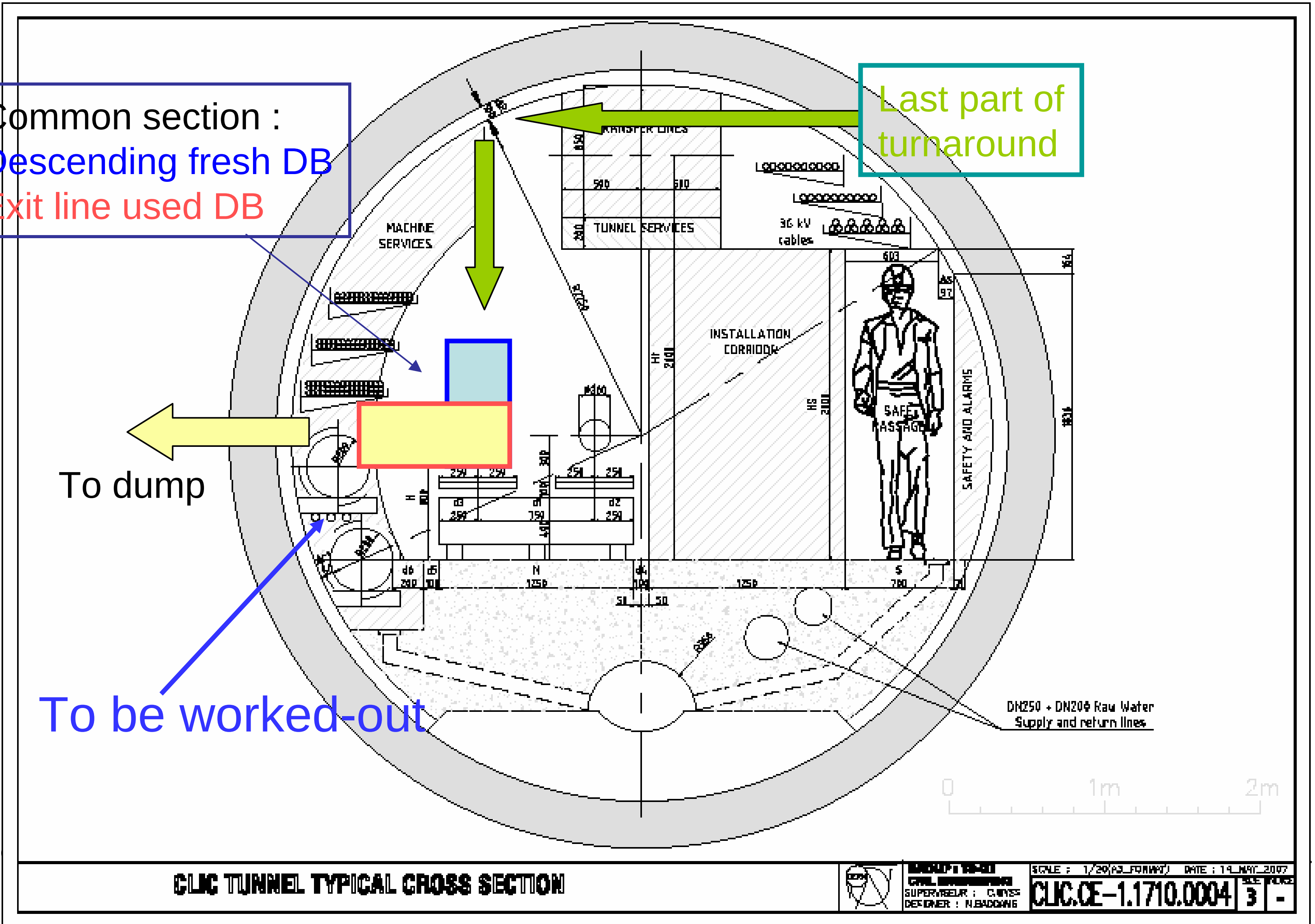
DB after the kicker

- Re-evaluate the best transverse position of the DBTL, i.e. move it towards the side ?
- Understand if the tunnel size and occupancy will change (new input for air and water, oct07)
- Make use of the kicker to cancel the dispersion wave of the TL, to avoid complications with chicanes

- 3D-model of the beam under work (Alexander Sumoshkin, Germana), optics of F.Stulle to be adapted

DUMP

Avoid magnets here



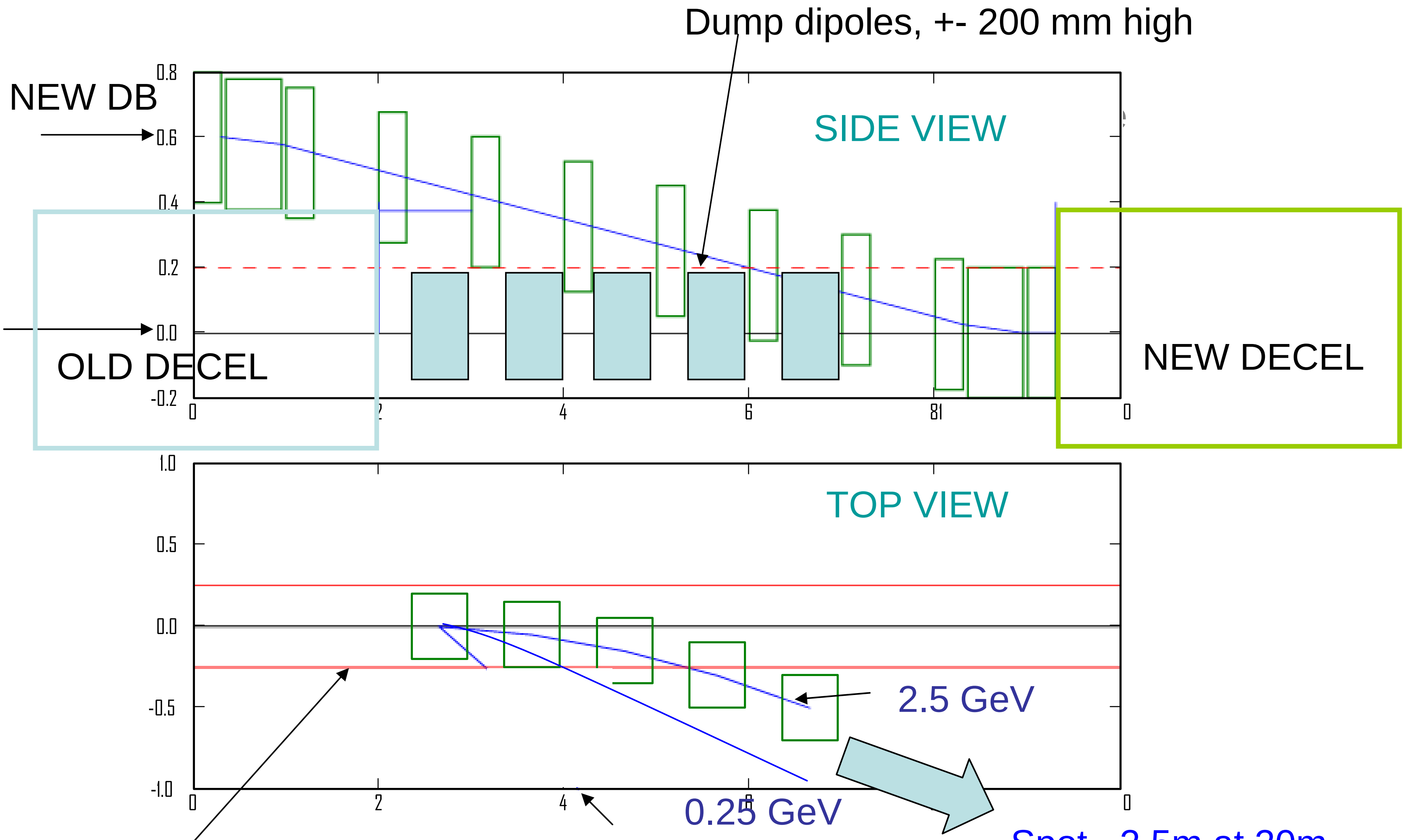
Common section :
Descending fresh DB
Exit line used DB

Last part of turnaround

To dump

To be worked-out

A way to avoid alternating low and high Decelerators – now baseline



Dump dipoles, +- 200 mm high

NEW DB

SIDE VIEW

OLD DECEL

NEW DECEL

TOP VIEW

2.5 GeV

0.25 GeV

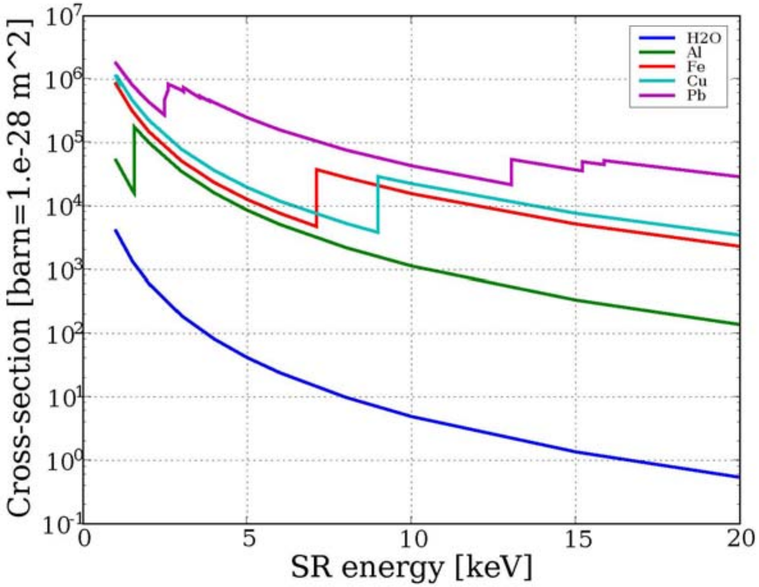
Spot ~2.5m at 20m on dump

Width of DB quads

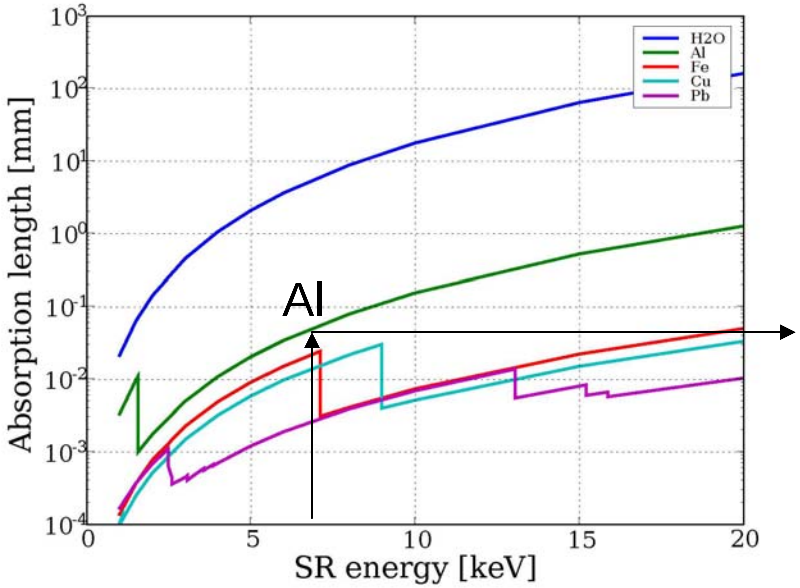
Combiner rings

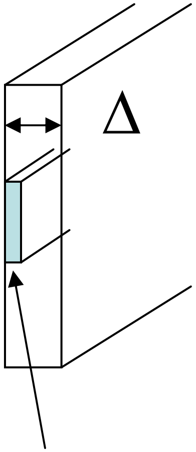
- Synchrotron radiation issues
- Open studies

SR issues - I



C1		
Bending radius	**5**	**m**
dE/E per turn	**1.2 10^{-5}**	**-**
Power/m	**1050**	**W/m**
Photon energy	**6.3**	**KeV**
Photon rate	**1.04 10^{18}**	**1/m/s**





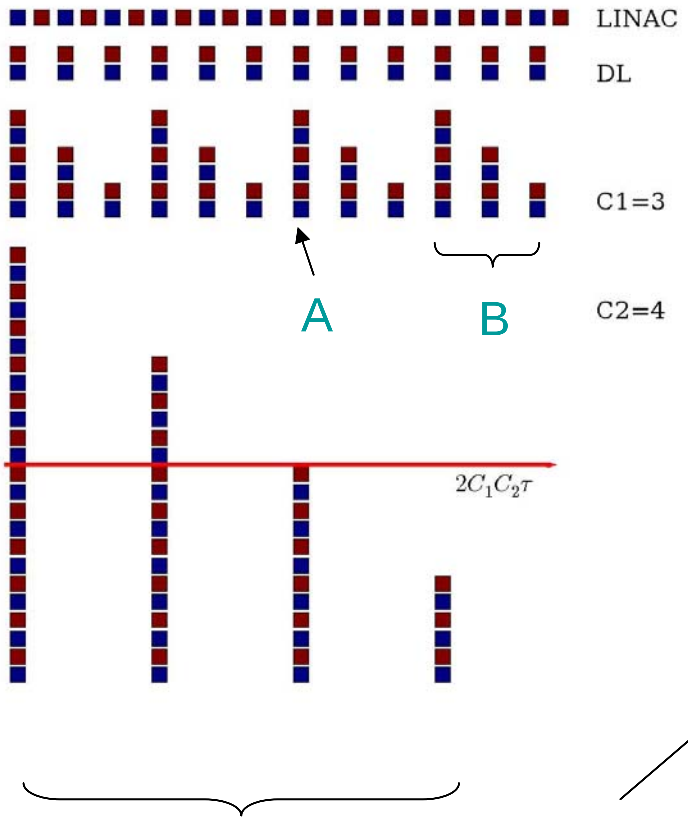
dy=10^{-3} m

Heated volume over dz=1m:
$V = dz\ dy\ (dx_{abs}^{2} + d_{diff}^{2})^{1/2}$

$d_{diff} \sim= (2Dt)^{1/2}$

6 KeV : $dx_{abs} = \alpha_{impact} \times 5\ 10^{-2} = 10^{-2}$ mm

SR issues - II



C : 24x

$t = 2NC_1C_2\tau$

C1		
Bending radius	**5**	**m**
dE/E per turn	**$1.2\ 10^{-5}$**	**-**
Power/m	**1050**	**W/m**
Photon energy	**6.3**	**KeV**
Photon rate	**$1.04\ 10^{18}$**	**1/m/s**

Pulse duration	tau	2.41E-07
C1		3
C2		4
Sectors	N	24
Aluminium		
Heat cap.	C	2.24E+06
Heat cond.	K	2.21E+02
Haet diff.	D	9.87E-05
Impact surface	S	1.00E-03

Fast adiabatic heat deposition / per magnet

Case	Q [J]	t [s]	x [m]	d [m]	V [m-3]	DT [K]
A	0.11	2.41E-07	1.00E-05	6.90E-06	1.21E-08	**4.0**
B	0.22	1.45E-06	1.00E-05	1.19E-05	1.56E-08	**6.2**
C	20.89	1.39E-04	1.00E-05	1.17E-04	1.17E-07	**79.4**

Steady heat transfer across vacuum chamber thickness,

Repetition rate	f	50	Hz
Per magnet			
Power	P [W]	1044	
Temp gradient : gradT=P/(SK)	[K/m]	4.73E+03	
Chamber thick.	x [m]	0.001	
Delta T = x gradT	[K]	4.7	

Very simple calculation, and bending radius may change

SR issues - III

- Crude SR study indicates:
  - SR is absorbed in a thin inner layer of the vacuum chamber

  → Transient temperature rise of the order $\Delta T = 80$ +- ? K at repetition frequency f=50Hz → ageing ...
  - Good vacuum requires getter at room temperature …

- → Need precise time-dependent thermal, mechanical and vacuum model , to be worked-out

- Coherent synchrotron radiation can/must be screened with adequately small vertical aperture , but possible conflict with wakefields reduction (large size, see above)

ESRF : I=100mA, E=6GeV, Power=3kW/m, E_γ=20KeV, λ=1mm

C1 : I_{av}=58mA, E=2.4GeV, Power=1.0kW/m, Eγ=6KeV, λ=0.05mm

Open studies for Delay Loop and Combiner Rings : (Fully-) Open studies

- Linear optics to be built for
  - Synchronous and chromatically-corrected rings
  - Then sensitivity/robustness studies
    - Tune + orbit errors → synchronicity errors
    - Tune error → β-beating → mismatch downstream, emittance growth

- Source of errors
  - EM collective effects (25→100A in four turns)
  - Ions production (vacuum degraded by SR)
    - $\Delta\nu$ growing along trains + instabilities ?

- Synchrotron radiation & Thermal issues
  - Coordinated studies with vacuum experts

Acknowledgments

- Marta Bajko , AT/MCS
- Pedro Costa Pinto , TS/MME
- Stephane Fartoukh
- Frank Stulle , PSI
- Giovanni Rumolo
- Thomas Zickler , AT/MEL ,

and my colleagues in ABP/CC3

Summary

- Long transfer line: well advanced
  - Need good (getter+bake-out) vacuum (ions)
  - **Vacuum chamber R >= 60mm, Al or Cu** (multi-bunch resistive wake-fields)
  - Cell with L =~ 100m , phase advance 45^o, with chromatic correction
    - to be fine-tuned with turn-around integration
  - A pre-design of a combined magnet exists – need consolidation, then overall cost optimisation
  - A MadX sequence can be ready in a near future

- Delay loop and Combiner rings
  - SR issues : dynamic thermal problems, to be explored precisely (also CSR/wake field/R_vac)
  - **Optics : entirely open area**

- Turnaround and compression:
  - good optics exists (F. Stulle), to be adapted to hardware constraints
  - **Integration to be fully made** (what is needed for 2010?)

- Dump line (and dump)
  - A ‘proof of existence’ exist which allows to avoid two heights of decelerator
  - Realistic study matched with the turnaround to be made
  - Dump proper : specify spent beam impact map

→ priorities to be established for 2010