DE LA RECHERCHE À L'INDUSTRIE

ETIC: ELECTRON TRAPPED ION COLLISIONS FOR 10^{29} LUMINOSITY

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On behalf of Jacques PAYET

ESNT workshop 25-27 April 2016

Electron-radioactive ion collisions: theoretical and experimental challenges

« ELECTRONS: PIÈGES À IONS! »

SLOGAN REVISITÉ, MAI 68, A. GILLIBERT

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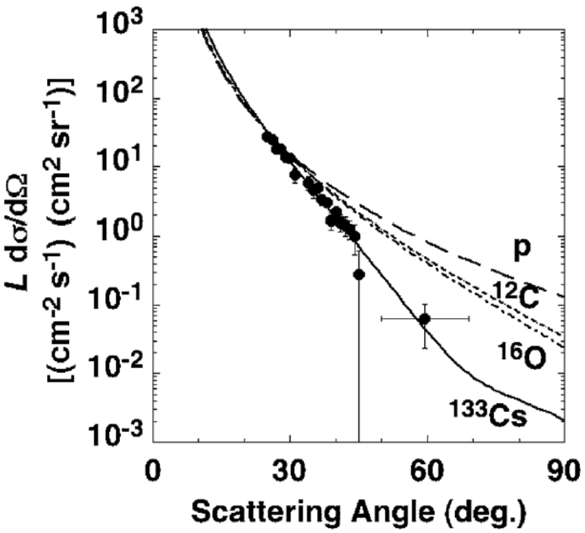
SUMMARY

SCRIT → ETIC

- <u>Kyoto prototype **confirmed the feasibility of SCRIT**</u>
  - Luminosity of 10^{26} $cm^{-2}s^{-1}$ achieved for 10^6 ions of stable ^{133}Cs
  - Injection-trap-ejection and detection systems tested
  - Elastic scattering from Cs ions unambiguously observed
- <u>SCRIT operative at RIKEN</u>
  - Physics runs in 2015-2016
  - Luminosity **limited to 10^{27-28} $cm^{-2}s^{-1}$** → mainly elastic scattering of mid/heavy nuclei



T. Suda *et al.*, Phys. Rev. Lett. **102**, 102501 (2009).

ETIC (Electron-Trapped Ion Collider)

- Working group started at CEA/IRFU within GANIL2025 discussions on a possible electron-ion collider started at CEA/IRFU
- SCRIT concept matches well GANIL settings (continuous injection / low energy)
- ETIC goal: gain a **factor > 100 in luminosity** w.r.t. SCRIT
  - ➘ Greatly expand accessible types of reactions and reach in N/Z
  - ➘ Open up exciting areas of potential physics research

LUMINOSITY

Geometric Luminosity

$$L_{geom} = \frac{n_{bunch}\, N_{RI} N_{e,bunch}}{4\pi\ \sigma_x \sigma_y\ t_{rev}} = \frac{I_{beam}\ N_{RI}}{4\pi\ \sigma_x \sigma_y\ q_e} = \frac{N_{RI}}{4\pi q_e \kappa \sqrt{\beta_x \beta_y}} \frac{I_{beam}}{\varepsilon_x}$$

$$\kappa = \frac{\varepsilon_y}{\varepsilon_x}$$

To reach the luminosity one can play on:

LUMINOSITY

Geometric Luminosity

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$$\kappa = \frac{\varepsilon_y}{\varepsilon_x}$$

To reach the luminosity one can play on:

- The trapped ions number N_{RI}.

LUMINOSITY

Geometric Luminosity

$$L_{geom} = \frac{n_{bunch} N_{RI} N_{e,bunch}}{4\pi\, \sigma_x \sigma_y\, t_{rev}} = \frac{I_{beam}\, N_{RI}}{4\pi\, \sigma_x \sigma_y\, q_e} = \frac{N_{RI}}{4\pi q_e \kappa \sqrt{\beta_x \beta_y}} \frac{I_{beam}}{\varepsilon_x}$$

$$\kappa = \frac{\varepsilon_y}{\varepsilon_x}$$

To reach the luminosity one can play on:

- The trapped ions number N_{RI}.
- The electron beam intensity I_{beam}.

Geometric Luminosity

$$L_{geom} = \frac{n_{bunch} N_{RI} N_{e,bunch}}{4\pi\, \sigma_x \sigma_y\, t_{rev}} = \frac{I_{beam}\, N_{RI}}{4\pi\, \sigma_x \sigma_y\, q_e} = \frac{N_{RI}}{4\pi q_e \kappa \sqrt{\beta_x \beta_y}} \frac{I_{beam}}{\varepsilon_x}$$

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To reach the luminosity one can play on:

- The trapped ions number N_{RI}.
- The electron beam intensity I_{beam}.
- The electron beam optics κ, β_x, β_y.

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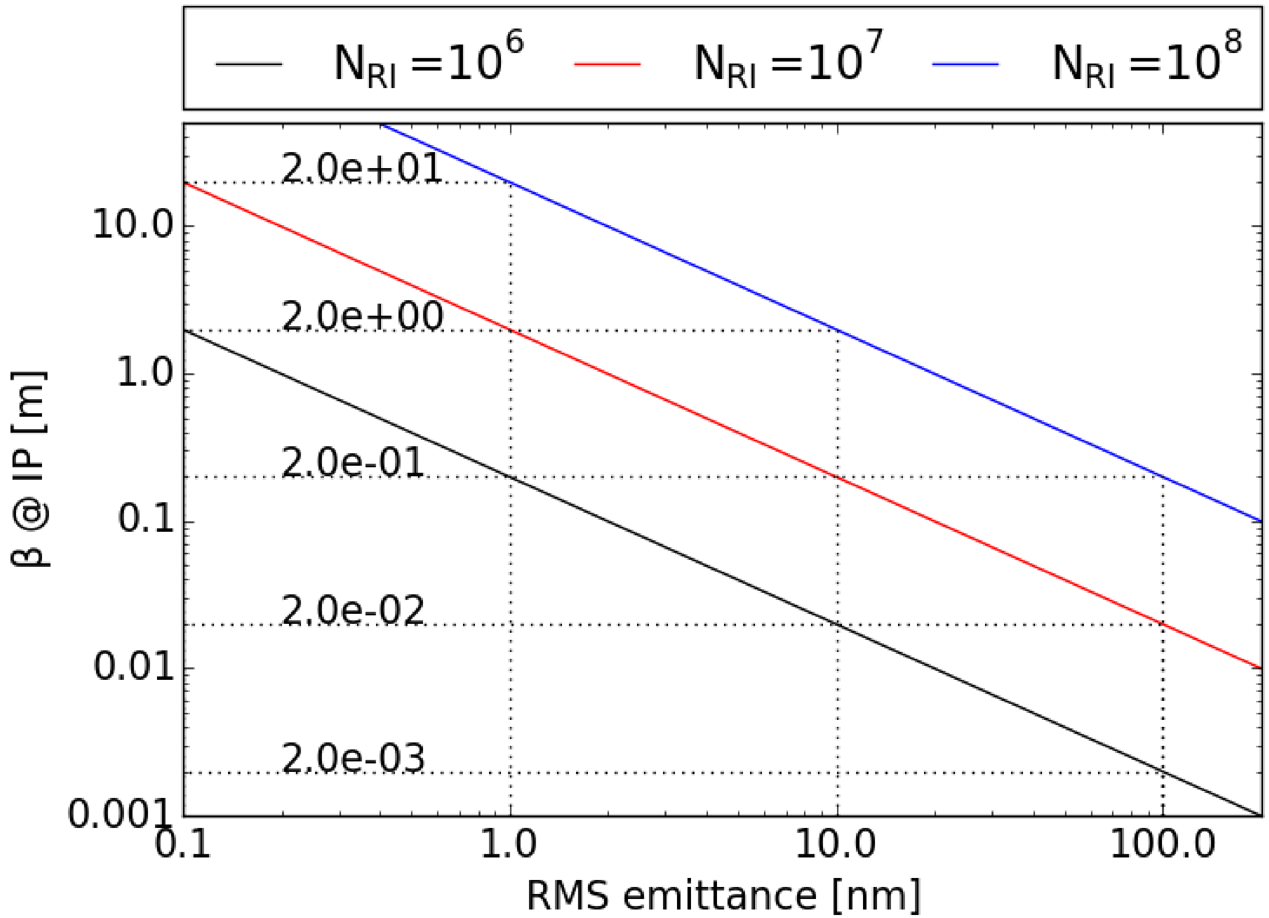
$$\kappa = \frac{\varepsilon_y}{\varepsilon_x}$$

To reach the luminosity one can play on:

- The trapped ions number N_{RI}.
- The electron beam intensity I_{beam}.
- The electron beam optics κ, β_x, β_y.
- The electron beam emittance ε_x.

ORDER OF MAGNITUDE

I_{beam}=200 mA, $L_{geom}=10^{29}$ $cm^{-2}s^{-1}$, κ=0.5



MAIN FEATURES

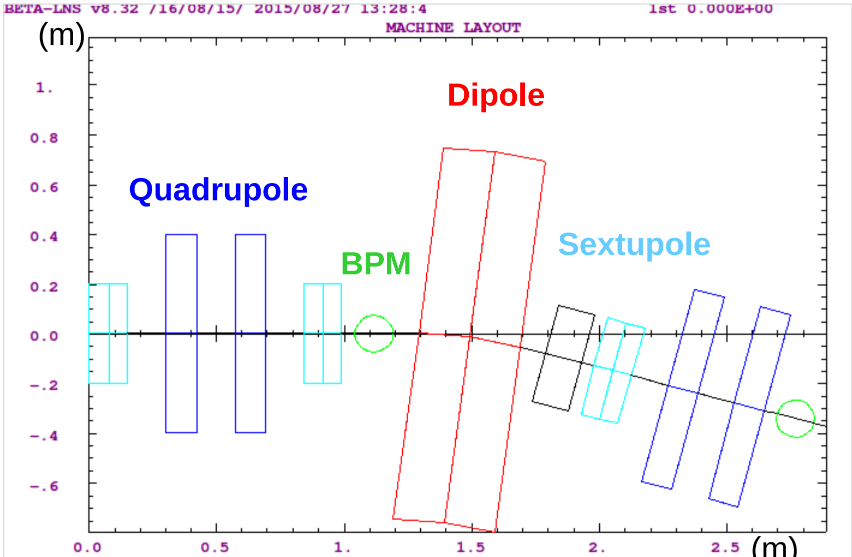
- Luminosity goal 10^{29} - 10^{30} $cm^{-2}s^{-1}$
- Working energy range 0.5-0.7 GeV
- 6 m long free space, at least, for e-Ions collisions
- Collider Interaction Region (like LHC, ILC)
- Racetrack shape, two long straight sections
- The experiment is located in one long straight section.

- Circular Accelerator
  - Adjustable equilibrium emittance from 4 nm down to 0.5 nm
  - Coupling 50%
  - Multiple Bend Achromat arc lattice

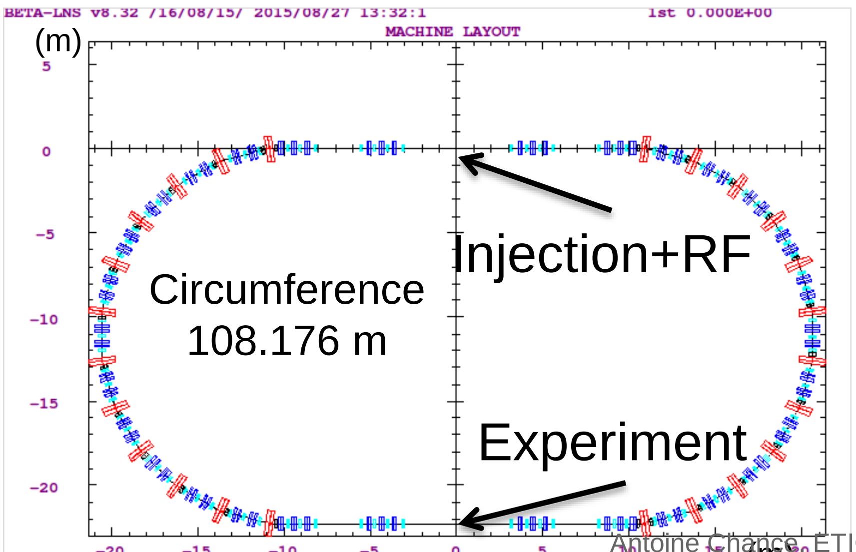
- Energy Recovery Linac
  - 1 nm emittance at working energy
  - Low emittance return arcs

CIRCULAR ACCELERATOR

MBA LATTICE V28, LAYOUT



Arc cell layout

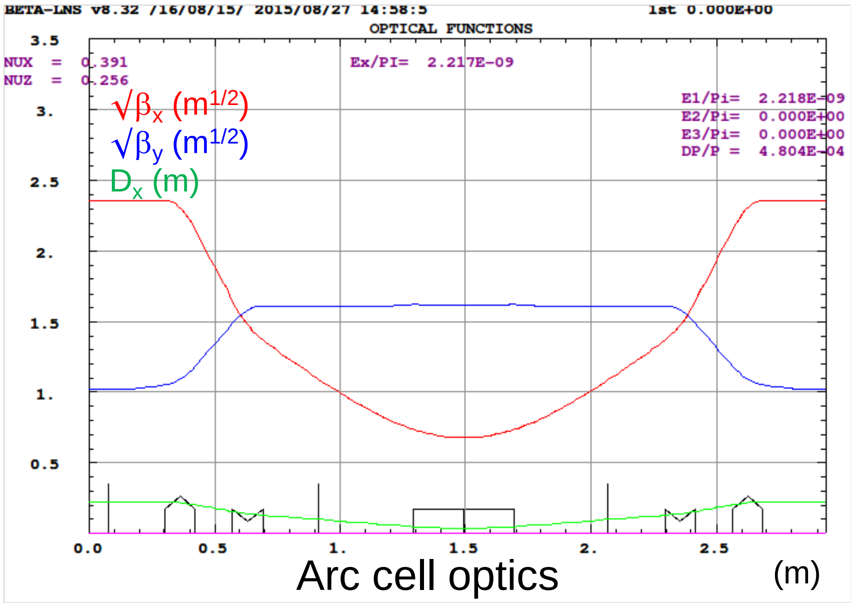


Ring layout

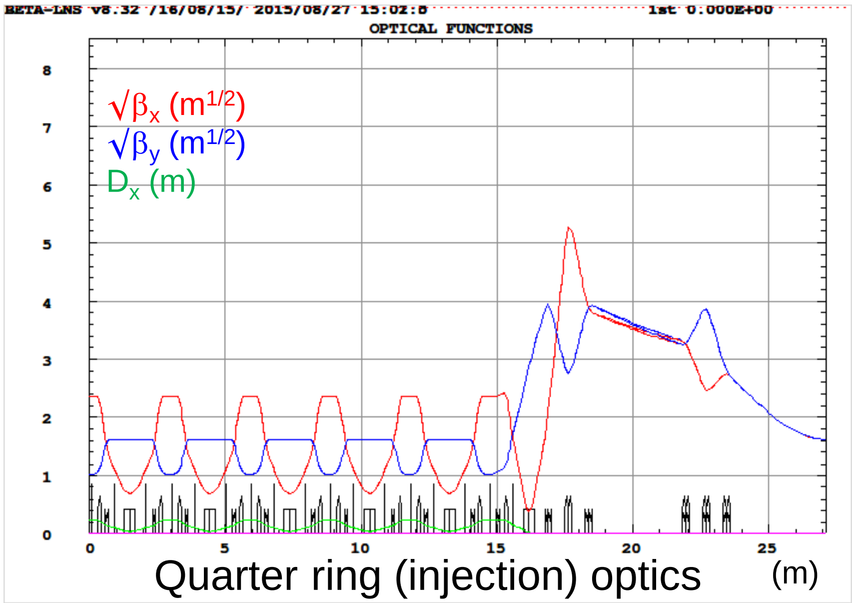
- The arcs are composed by **12 cells** which form a **Multiple Bend Achromat**.
- The arc cell is composed by one dipole surrounded by four quadrupoles.
- Two arc quadrupole families allow to **adjust the equilibrium emittance**.
- Chromaticity corrected by 2 sextupole families.
- Additional dipolar windings in the sextupoles allow to correct the orbit.
- The first and last cells of the arcs are dispersion suppressors.

Element	Length (m)	#nb
Dipole	0.4033 + 0.2	24
Quadrupole 1	0.12 + 0.10	88
Quadrupole 2	0.26 + 0.13	24
Sextupole	0.15 + 0.10	94
BPM	0.15	56
Bellow	0.15	26

MBA LATTICE V28, 2.0 NM OPTICS

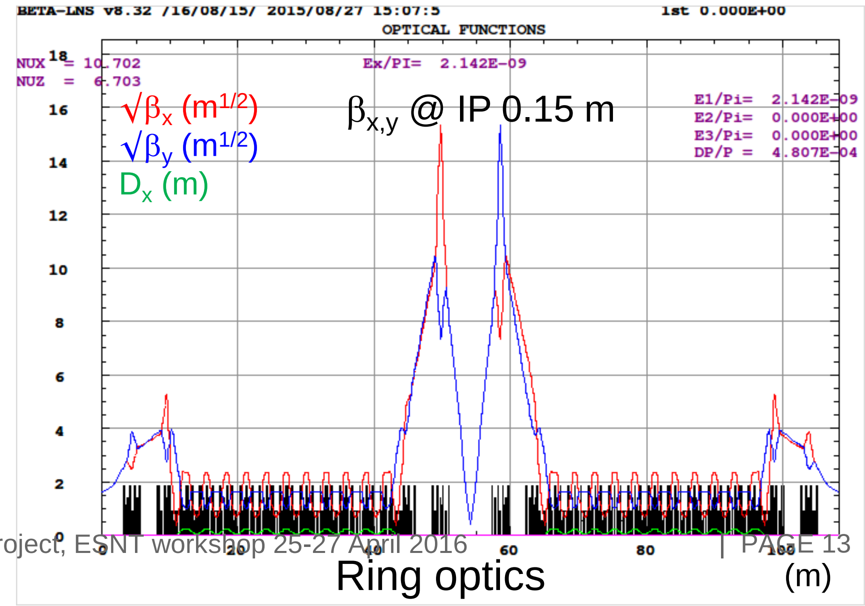


Arc cell optics



Quarter ring (injection) optics

The focusing is reverted from either side of the straight section centers in order to balance the horizontal and vertical chromaticity.



Ring optics

MBA LATTICE V28, TUNING PARAMETERS

Tuning	1 nm @ 700 MeV		1.5 nm @ 700 MeV		2 nm @ 700 MeV	
Circumference (m)	108.176					
Ec (MeV)	500	700	500	700	500	700
ε_x (nm.rad)	0.59	1.16	0.76	1.49	1.09	2.14
κ Coupling (%)	50					
$\beta_{x,y}$ @ IP (m)	0.3, 0.3		0.2, 0.2		0.15, 0.15	
$\sigma_{x,y}$ @ IP (μm)	13.4, 9.4	18.7, 13.2	12.3, 8.7	17.3, 12.2	12.8, 9.1	17.9, 12.7
σ_δ (%)	0.0344	0.0482	0.0344	0.0481	0.0343	0.0481
σ_s (mm)	4.43	5.80	4.46	5.88	4.52	6.02
V_{RF} (kV)	58	94	68	108	87	135
$Q_{x,y}$	11.702, 6.685		11.300, 6.308		10.702, 6.703	
Chromaticity $_{x,y}$	-4.41, -2.59		-3.73, -3.17		-3.50, -3.53	
D_x max (m)	0.200		0.205		0.221	
I_{beam} (mA)	254	499	217	423	233	458

The 10^{29} $cm^{-2}s^{-1}$ luminosity goal is reached with 10^6 trapped ions

SC TUNE SHIFT : SC LINEARIZED STRENGTH

The particles undergo a repulsive force due to the Coulomb interaction with the beam. Due to this force, the betatron tunes of the particles are dispersed over a certain range.

Linear approximation

$$E_x \approx \frac{q_e\,\lambda}{2\pi\varepsilon_0}\frac{x}{\sigma_x\left(\sigma_x+\sigma_y\right)}, E_y \approx \frac{q_e\,\lambda}{2\pi\varepsilon_0}\frac{y}{\sigma_y\left(\sigma_x+\sigma_y\right)}$$

$q_e\lambda$ is the longitudinal charge density

SC Tune Shift

$$\Delta Q_{x,y\;SC} = \frac{\mp 1}{2\pi}\oint \beta_{x,y}k_{x,y}ds, \qquad k_{x,y} = -\frac{2\,r_e\,\lambda}{\beta^2\,\gamma^3\sigma_{x,y}\,\left(\sigma_x+\sigma_y\right)}$$

For a Gaussian bunch of $N_{e,bunch}$ particles and rms bunch length σ_s the SC tune shift is given by:

$$\Delta Q_{x,y\;SC} = \frac{2r_e N_{e,bunch}}{(2\pi)^{3/2}\sigma_s\beta^2\gamma^3}\oint \frac{\beta_{x,y}}{\sigma_{x,y}\,\left(\sigma_x+\sigma_y\right)}ds$$

SC Laslett Tune Shift

$$\Delta Q_{x,y\,SC} = \frac{3\, r_e\, R_0 N_{e,bunch}}{4\beta^2\, \gamma^3 \varepsilon_{x,y}\, l_{bunch}} = \frac{3\, r_e\, R_0 t_{rev}}{4\beta^2\, \gamma^3\, q_e n_{bunch} l_{bunch}} \frac{I_{beam}}{\varepsilon_{x,y}}$$

The RF voltage, V_{RF}, is set in order to obtain the same momentum acceptance. Then, the bunch lengths are comparable for all equilibrium emittances.

The luminosity and the space charge tune shift remains constant when $I_{beam}/\varepsilon_{x,y}$ is constant.

SC TUNE SHIFT

ε_x=1.16 nm, δ_{RF}=0.02, h=123, $\beta_{x,y}$=0.30 m, N_{RI}=10^6, L_0= 10^{29} cm^{-2} s^{-1}				
E_c (MeV)	500	600	700	750
$N_{e,bunch}$ (10^9)	4.527	6.523	8.822	10.105
$\Delta Q_{x,y}$ (10^{-2})	-2.88, -4.88	-1.54, -2.49	-1.01, -1.58	-0.83, -1.29
$\Delta Q_{x,y}$ Laslett (10^{-2})	**-2.16, -4.31**	**-1.08, -2.15**	**-0.60, -1.20**	**-0.46, -0.93**
ε_x=1.49 nm, δ_{RF}=0.02, h=123, $\beta_{x,y}$=0.20 m, N_{RI}=10^6, L_0= 10^{29} cm^{-2} s^{-1}				
E_c (MeV)	500	600	700	750
$N_{e,bunch}$ (10^9)	3.868	5.579	7.539	8.644
$\Delta Q_{x,y}$ (10^{-2})	-1.85, -3.37	-0.98, -1.71	-0.34, -0.67	-0.22, -0.44
$\Delta Q_{x,y}$ Laslett (10^{-2})	**-1.43, -2.86**	**-0.71, -1.42**	**-0.39, -0.79**	**-0.30, -0.61**
ε_x=2.16 nm, δ_{RF}=0.02, h=123, $\beta_{x,y}$=0.15 m, N_{RI}=10^6, L_0= 10^{29} cm^{-2} s^{-1}				
E_c (MeV)	500	600	700	750
$N_{e,bunch}$ (10^9)	4.206	6.06	8.198	9.393
$\Delta Q_{x,y}$ (10^{-2})	-0.77, -1.60	-0.42, -0.84	-0.24, -0.46	-0.19, -0.36
$\Delta Q_{x,y}$ Laslett (10^{-2})	**-1.07, -2.13**	**-0.53, -1.05**	**-0.29, -0.58**	**-0.22, -0.45**

TOUSCHEK EFFECT

Touschek effect is a **loss mechanism:**

Large angle Coulomb collisions in the bunch

$\Rightarrow$ **Momentum transfers** into the **longitudinal** plane.

$\Rightarrow$ Change of the betatron amplitudes if occurs in dispersive areas.

$\Rightarrow$ Loss of the particles if:

- $\Rightarrow$ the momentum exceeds the RF acceptance or
- $\Rightarrow$ if the transverse extensions exceed the acceptance (physical or dynamic).

The half life at a location *s* is given by

$$\frac{1}{\tau_{1/2}(s)} = \frac{c\, r_e{}^2\, N_{e,bunch}}{8\,\pi\,\sigma_x\,\sigma_y\,\sigma_s}\,\frac{D(\xi)}{\gamma^2 \delta_{RF}{}^2}$$

$$D(\xi) = \sqrt{\xi}\left\{-\frac{3}{2}e^{-\xi} + \frac{\xi}{2}\int_{\xi}^{\infty}\frac{\ln(u)}{u}e^{-u}\,du + \frac{3\xi - \xi\ln(\xi) + 2}{2}\int_{\xi}^{\infty}\frac{e^{-u}}{u}\,du\right\} \quad \xi = \left(\frac{\delta_{RF}\,\beta_x}{\gamma\,\sigma_x}\right)^2$$

The total half life is the average around the ring

$$\frac{1}{\tau_{1/2}} = \frac{1}{C}\oint\frac{ds}{\tau_{1/2}(s)}$$

TOUSCHEK LIFETIME

ε_x=1.16 nm, δ_{RF}=0.02, h=123, $\beta_{x,y}$=0.30 m, $N_{RI}=10^6$, $L_0= 10^{29}$ cm^{-2} s^{-1}				
E_c (MeV)	500	600	700	750
I_{beam} (mA)	254	366	495	567
$N_{e,bunch}$ (10^9)	4.527	6.523	8.822	10.105
$\tau_{Touschek}$ (h)	0.95	1.15	1.46	1.66
ε_x=1.49 nm, δ_{RF}=0.02, h=123, $\beta_{x,y}$=0.20 m, $N_{RI}=10^6$, $L_0= 10^{29}$ cm^{-2} s^{-1}				
E_c (MeV)	500	600	700	750
I_{beam} (mA)	217	313	423	485
$N_{e,bunch}$ (10^9)	3.868	5.579	7.539	8.644
$\tau_{Touschek}$ (h)	1.25	1.54	2.01	2.31
ε_x=2.16 nm, δ_{RF}=0.02, h=123, $\beta_{x,y}$=0.15 m, $N_{RI}=10^6$, $L_0= 10^{29}$ cm^{-2} s^{-1}				
E_c (MeV)	500	600	700	750
I_{beam} (mA)	236	340	460	527
$N_{e,bunch}$ (10^9)	4.206	6.060	8.198	9.393
$\tau_{Touschek}$ (h)	1.35	1.74	2.38	2.79

Intra-beam scattering: multiple Coulomb scattering

⇒ Diffusion in all three directions

⇒ Changes the beam dimensions.

⇒ We get the growth rates for the 3 degrees of freedom by computing the momentum variation by scattering in between the beam particles.

$$\begin{cases} \dfrac{d\varepsilon_{x,y}}{dt} = -\dfrac{2}{\tau_{x,y}}\left(\varepsilon_{x,y} - \varepsilon_{x,y,0}\right) + \dfrac{2\varepsilon_{x,y}}{T_{x,y}\left(\varepsilon_x, \varepsilon_y, \sigma_\delta\right)} \\ \dfrac{d({\sigma_\delta}^2)}{dt} = -\dfrac{2}{\tau_\delta}\left({\sigma_\delta}^2 - {\sigma_{\delta 0}}^2\right) + \dfrac{2{\sigma_\delta}^2}{T_\delta\left(\varepsilon_x, \varepsilon_y, \sigma_\delta\right)} \end{cases}$$

where $\begin{cases} T_{x,y,\delta}\left(\varepsilon_x, \varepsilon_y, \sigma_\delta\right) \text{ are the IBS growth rates} \\ \tau_{x,y,\delta} \text{ are the synchrotron radiation damping times} \\ \varepsilon_{x,y,0}, \sigma_{\delta 0} \text{ are the zero current emittances and momentum spread} \end{cases}$

Equilibrium emittance is reached when the SR damping counterbalances the emittance growing.

$$\frac{d\varepsilon_{x,y}}{dt} = 0, \frac{d({\sigma_\delta}^2)}{dt} = 0$$

INTRA-BEAM SCATTERING : W/O BUNCH LENGTHENING

$N_{RI}=10^6$, $L_0= 10^{29}$ cm^{-2} s^{-1}

Ec (MeV)	500			600			700		
Approximation	Bane	MAX IV	CIMP	Bane	MAX IV	CIMP	Bane	MAX IV	CIMP
1.0 nm tuning	$\varepsilon_{x,0}$ = 0.59 nm, $\sigma_{\delta,0}$ = 3.4 10^{-4}			$\varepsilon_{x,0}$ = 0.86 nm, $\sigma_{\delta,0}$ = 4.1 10^{-4}			$\varepsilon_{x,0}$ = 1.16 nm, $\sigma_{\delta,0}$ = 4.8 10^{-4}		
$T_{x,y}$ (ms)	X	X	X	X	X	X	140	138	108
T_δ (ms)	X	X	X	X	X	X	50	49	46
$\varepsilon_{x,y}$ (nm)	X	X	X	X	X	X	1.58, 0.79	1.59, 0.80	1.78, 0.58
σ_δ (10^{-4})	X	X	X	X	X	X	6.0	6.1	6.2
1.5 nm tuning	$\varepsilon_{x,0}$ = 0.76 nm, $\sigma_{\delta,0}$ = 3.4 10^{-4}			$\varepsilon_{x,0}$ = 1.10 nm, $\sigma_{\delta,0}$ = 4.1 10^{-4}			$\varepsilon_{x,0}$ = 1.49 nm, $\sigma_{\delta,0}$ = 4.8 10^{-4}		
$T_{x,y}$ (ms)	X	X	X	X	X	X	218	221	166
T_δ (ms)	X	X	X	X	X	X	62	62	58
$\varepsilon_{x,y}$ (nm)	X	X	X	X	X	X	1.80, 0.90	1.79, 0.90	1.92, 0.75
σ_δ (10^{-4})	X	X	X	X	X	X	5.7	5.7	5.8
2.0 nm tuning	$\varepsilon_{x,0}$ = 1.09 nm, $\sigma_{\delta,0}$ = 3.4 10^{-4}			$\varepsilon_{x,0}$ = 1.57 nm, $\sigma_{\delta,0}$ = 4.1 10^{-4}			$\varepsilon_{x,0}$ = 2.14 nm, $\sigma_{\delta,0}$ = 4.8 10^{-4}		
$T_{x,y}$ (ms)	X	X	X	231	236	175	381	404	286
T_δ (ms)	X	X	X	57	58	54	75	79	73
$\varepsilon_{x,y}$ (nm)	X	X	X	2.12, 1.06	2.11, 1.05	2.38, 0.79	2.38, 1.19	2.36, 1.18	2.47, 1.07
σ_δ (10^{-4})	X	X	X	5.8	5.8	6.0	5.5	5.5	5.5

CIRCULAR ACCELERATOR CONCLUSIONS

- With 10^6 trapped ions, the 10^{29} $cm^{-2}s^{-1}$ **luminosity goal is reached** with a conventional electron circular accelerator.

- For **500-600 MeV** working energy range, a good compromise between optics and equilibrium emittance seems the lattice “**2.0 nm tuning**”, which leads to the lowest space charge tune shift and the lowest IBS growth.

- The Touschek life time remains short, but compatible with the experiments.

- The **IBS is an issue** and we have to consider a bunch lengthening with harmonic cavities, this will have a positive effect on the SC tune shift and on the Touschek life time.

- An **increase of the number of trapped ions** will allow to reduce the electron beam intensity :
  - the IBS growth will decrease,
  - the Touschek life time will increase,
  - the SC tune shift will decrease.

ENERGY RECOVERY LINAC

ADVANTAGES OF AN ERL

Advantage of ERL vs Storage Ring

- Non-equilibrium conditions (IBS, Touschek life-time,…)
  - All of this is particularly important at low energy (300-500 MeV)

- Beam characteristics determined by injector
  - Small emittance, Ultra short bunches

- The difficulties inherent to the circular machines have no more place
  - Dynamic aperture, Resonances crossing

Advantage of ERL vs Linacs

- Improvement in efficiency
  - An ERL is less expensive in exploitation cost
  - Increase in average current (CW)

- Reduced beam dump activation

CHALLENGES

- **High current & low emittance beam production**
  - Source, injector
- **Emittance control**
  - Emittance growth due to SR
- **Beam/orbit stability**
  - Sub-micro stability (rms) is required
  - 10^{-4} energy stability is needed
- **SRF issues**
  - HOM damping
  - RF cavity design, high Q_0 cavity
- **Collective effects**
  - Beam break-up (BBU) instability
- **Instrumentation & diagnostics**

PARAMETERS

Many challenges

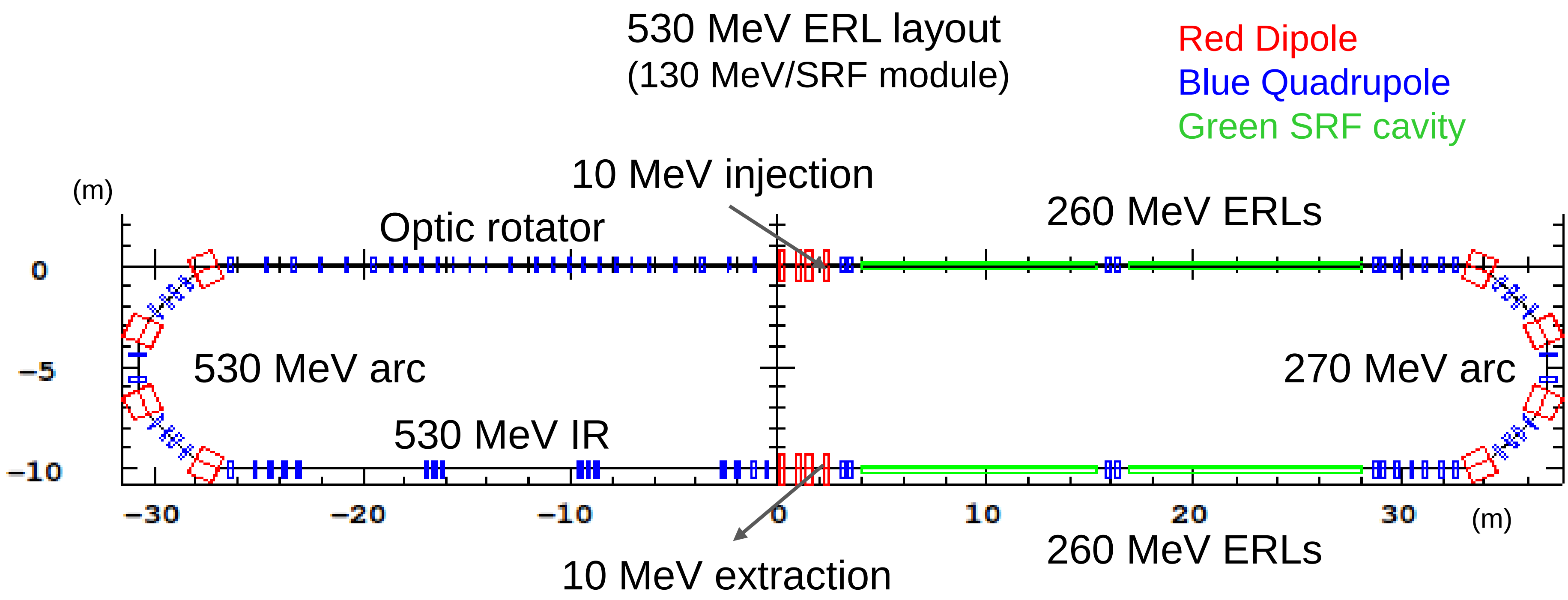
$\varepsilon_N = \beta \gamma \varepsilon(E_c)$

Injector Parameters	
Energy (MeV)	10
Charge per bunch (pC)	77
Normalized Emittance (mm.mrad)	1
Bunch length rms (ps)	2
Repetition Rate (CW, MHz)	1300
I_{beam} (mA)	100

ERL, IR Parameters	
Injection/Extraction energy (MeV)	10
Beam dump power (MW)	1
Energy max. (MeV)	530
Beam power @ 530 MeV (MW)	53
Emittance @ 500 MeV (nm.rad)	1.02
$\beta_{x,y}$ @ IP (m)	0.048
Beam size @ IP (μm)	7

With $N_{RI}=10^6 \Rightarrow L_0=10^{29}$ $cm^{-2}s^{-1}$

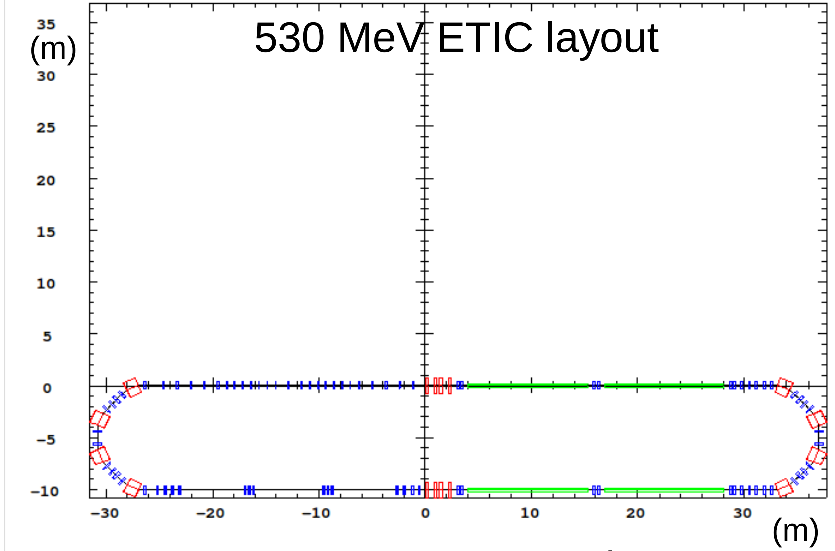
SCHEMATIC LAYOUT

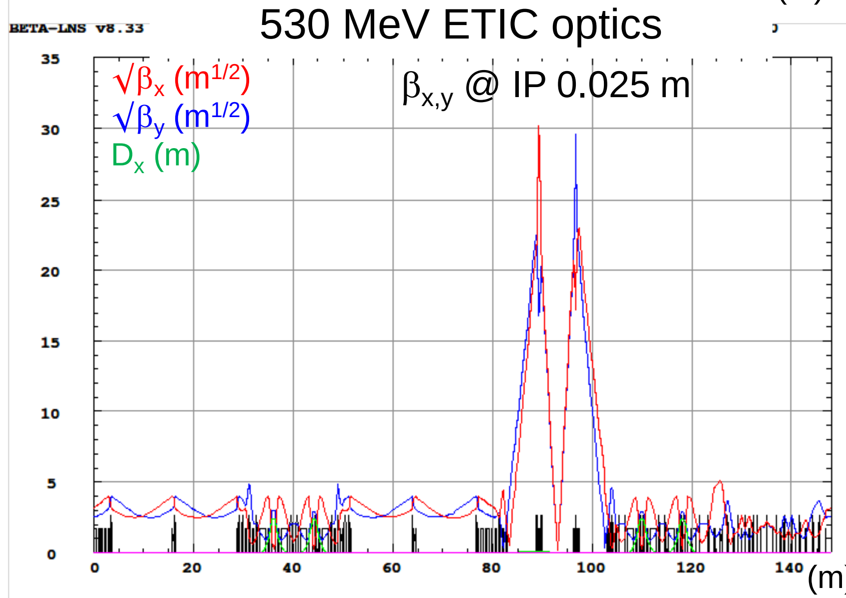


ETIC 530 MeV:

- -4 accelerator modules
- -interaction region @ 530 MeV
- -return optic not yet considered
- -dogleg is not yet considered

Circumference (m)	147.85
Footprint (m x m)	70 x 12
E_c (MeV)	530
N_{RI} (10^6)	1
Emittance @ 530 MeV (nm.rad)	0.96
$\beta_{x,y}$ @ IP (m)	0.05 — 0.025
Size @ IP (μm)	6.9 — 4.9
L_0 /IP @ 530 MeV (10^{29} $cm^{-2}s^{-1}$)	1.03 — 2.06



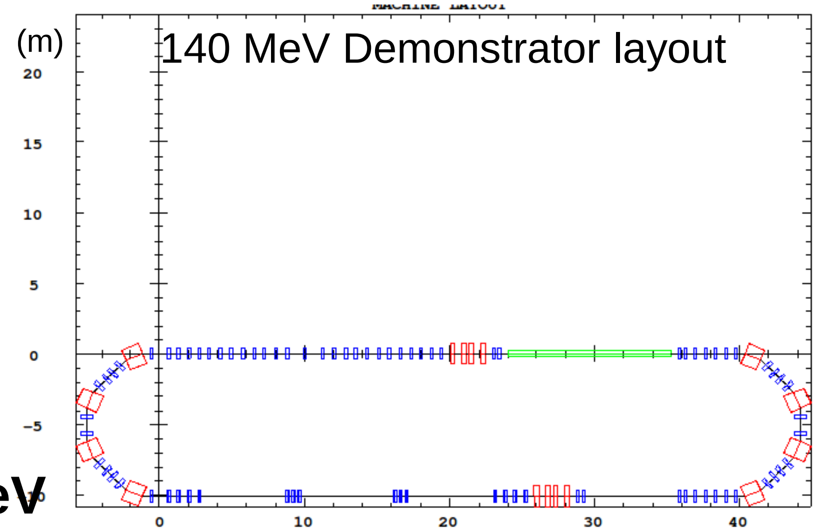


140 MEV DEMONSTRATOR PRELIMINARY LAYOUT

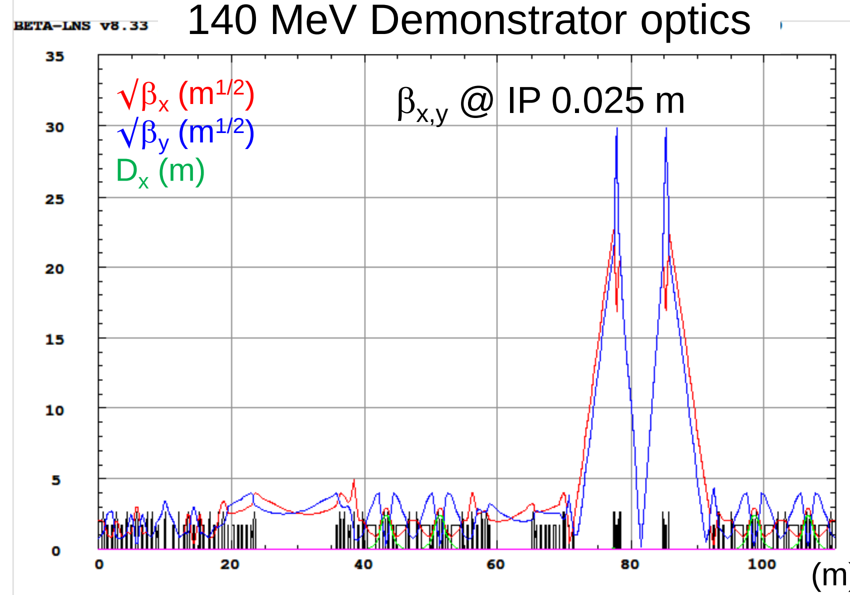
To validate these challenges:

- electron source
- energy recovering
- BBU cure capability
- ion trapping
- emittance control
- Optics

⇒ **Proposal of a demonstrator 140 MeV**



140 MeV Demonstrator optics



Circumference (m)	110.62
Footprint (m x m)	52 x 12
E_c (MeV)	140
N_{RI} (10^6)	1
Emitttance @ 140 MeV (nm.rad)	3.9
$\beta_{x,y}$ @ IP (m)	0.05 — 0.025
Size @ IP (µm)	14 — 9.9
L_0 /IP @ 140 MeV (10^{29} $cm^{-2}s^{-1}$)	0.25 — 0.51

ERL
CONCLUSIONS

With 10^6 trapped ions, the 10^{29} $cm^{-2}s^{-1}$ luminosity goal can be **reached** with a **530 MeV ERL** accelerator.

An ERL is an interesting solution because **it does not have the circular machines related issues**. This is particularly important at low energy.

However **an increase of the trapped ions will be greatly appreciated**.

When the needed electron beam intensity becomes lower
$\Rightarrow$ The electron source parameters can be relaxed.

A 140 MeV ERL demonstrator can be a first step.

GENERAL CONCLUSIONS

- The aim of ETIC is to push the **luminosity to 10^{29}** by using a scheme a la SCRIT (circulating electron bunch which collided with trapped ions).

- Two options were explored:
  - A circular collider, which can work up to 700 MeV. A first optics was delivered. The main limitation comes from the intra beam scattering. At low energy (less than 700 MeV), the **IBS becomes an issue**. It limits the stored intensity and thus the luminosity. A solution is to use harmonic cavities to make RF gymnastics. That is a more expensive and needs more studies.

  - An electron recirculating linac (ERL). The IBS is not anymore a problem and we can work at lower energy. A first layout has been shown at 530 MeV. A special effort must be performed on the **electron source quality**.

- In both cases, a key point is the **ion capture efficiency**. The more efficient the capture is, the less intensity we need. The parameters can be then relaxed.

- That is why a proposal of an intermediary step was made with a **140 MeV demonstrator** to validate some of the key points of such a machine.

Thank you for your attention.

MBA LATTICE V28, MAGNETS

2 quadrupole types

Quadrupoles @ 750 MeV	
#nb	24
Bore Diameter ∅ (mm)	100
Magnetic length (m)	0.26
Gradient G (T/m)	13.8
#nb	88
Bore Diameter ∅ (mm)	56
Magnetic length (m)	0.12
Gradient G (T/m)	32.6

Bend @ 750 MeV	
#nb	24
Bore Diameter ∅ (mm)	56
Magnetic length (m)	0.4033
Field B (T)	1.625
Gradient G (T/m)	0

2 sextupole families

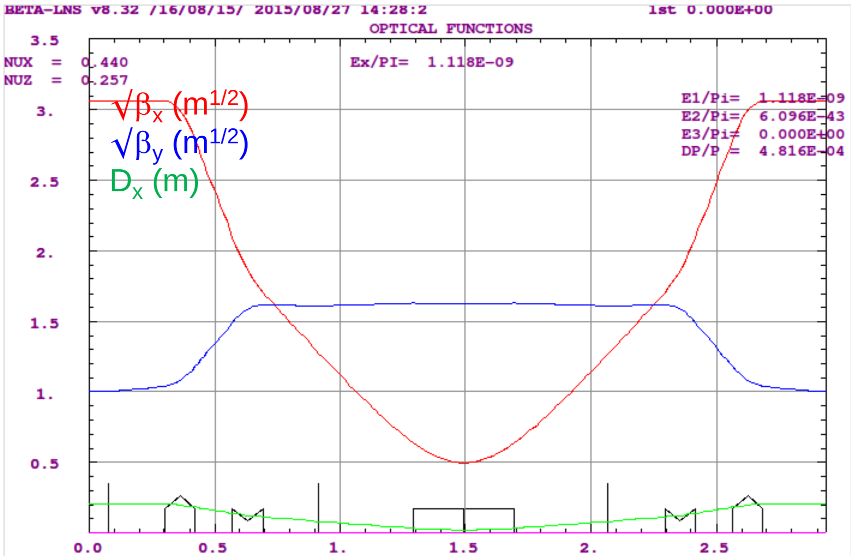
Sextupoles @ 750 MeV	
#nb	94
Bore Diameter ∅ (mm)	56
Magnetic length (m)	0.15
$1/2\ d^2B_y/dx^2$ (T/m^2)	305.5

MBA LATTICE V28, 1.0 NM PARAMETERS

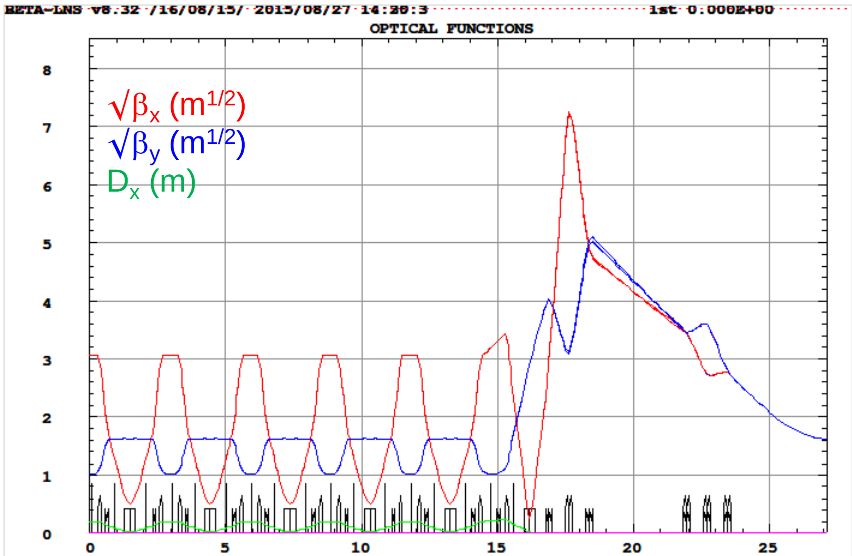
Circumference (m)	108.176
L bend (m)	0.4033
ρ bend (m)	1.5407
n bend=$-\rho/B_0\, dB_y/dx$	0
β_x , β_y @ IP (m)	0.3, 0.3
D_x max (m)	0.200
Q_x , Q_y	11.702,6.685
Q_x , Q_y arc cell	0.440, 0.257
$\xi_{x,y}=1/Q_{x,y}\, dQ_{x,y}/d\delta$	-4.41, -2.59
$l/(2B\rho)\, d^2B_y/dx^2$ (m^{-2})	10.82,-15.37
t_{rev} (ns)	360.8
RF frequency (MHz)	352
h, n_{bunch}	127, 127
α_c	1.31 10^{-3}
N_{RI} (10^6)	1

E_c (MeV)	500	700
B field (T)	1.0846	1.5167
ε_x (nm)	0.59	1.16
σ_x @ IP (μm)	13.35	18.68
σ_y @ IP (μm) κ=.50	9.44	13.21
V_{RF} (kV)	58	94
δ_{RF} (%)	2.	2.
σ_δ (%)	0.0344	0.0482
σ_s (mm)	4.43	5.80
τ_x (ms)	102.05	37.19
τ_s (ms)	49.91	18.19
I_{beam} (mA)	254	499
(ΔQ_x SC)	0.0221	0.0062
(ΔQ_y SC)	0.0441	0.0124
L_0 ($cm^{-2}s^{-1}\, 10^{29}$)	1	1

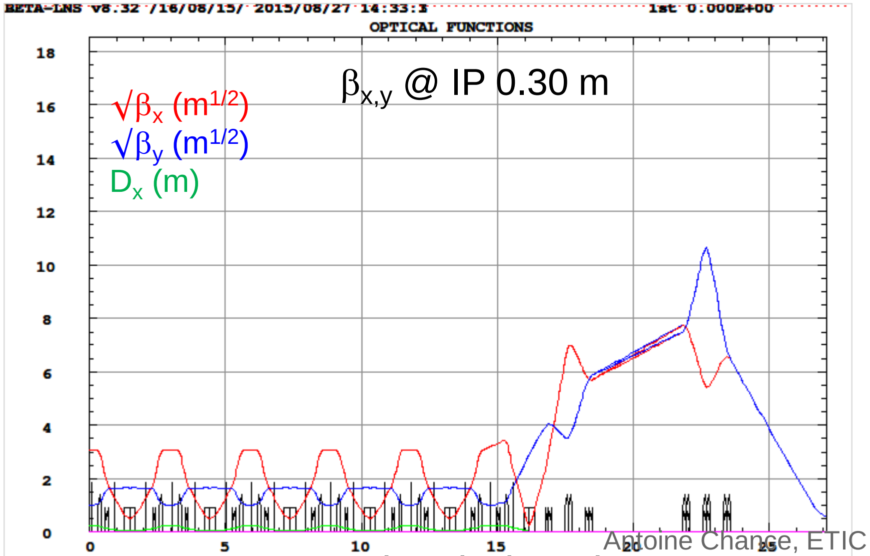
MBA LATTICE V28, 1.0 NM OPTICS



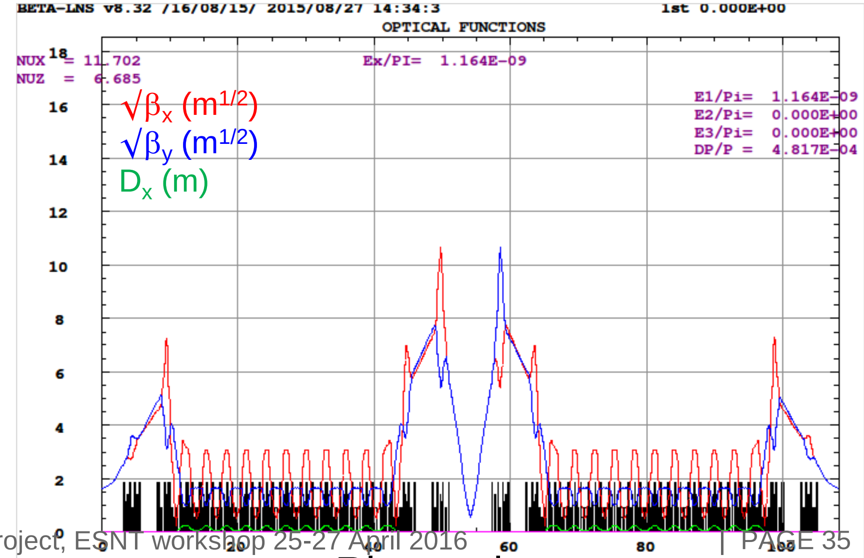
Arc cell optics



Quarter ring (injection) optics



Quarter ring (IR) optics



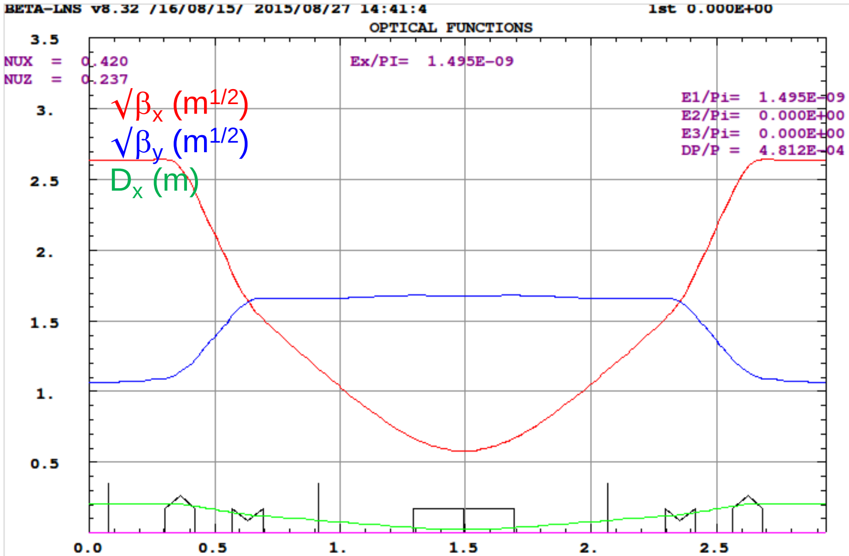
Ring optics

MBA LATTICE V28, 1.5 NM PARAMETERS

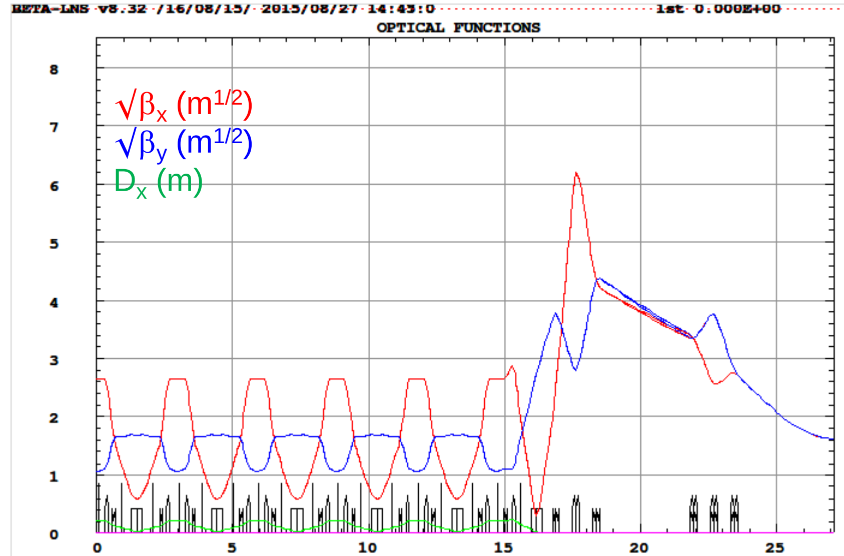
Circumference (m)	108.176
L bend (m)	0.4033
ρ bend (m)	1.5407
n bend=$-\rho/B_0\ dB_y/dx$	0
β_x , β_y @ IP (m)	0.2, 0.2
D_x max (m)	0.205
Q_x , Q_y	11.300,6.308
Q_x , Q_y arc cell	0.420, 0.237
$\xi_{x,y}=1/Q_{x,y}\ dQ_{x,y}/d\delta$	-3.73, -3.17
$l/(2B\rho)\ d^2B_y/dx^2\ (m^{-2})$	12.14,-16.80
t_{rev} (ns)	360.8
RF frequency (MHz)	352
h, n_{bunch}	127, 127
α_c	1.56 10^{-3}
N_{RI} (10^6)	1

E_c (MeV)	500	700
B field (T)	1.0846	1.5167
ε_x (nm)	0.76	1.49
σ_x @ IP (μm)	12.34	17.27
σ_y @ IP (μm) κ=.50	8.72	12.21
V_{RF} (kV)	68	108
δ_{RF} (%)	2.	2.
σ_δ (%)	0.0344	0.0481
σ_s (mm)	4.46	5.88
τ_x (ms)	102.33	37.29
τ_s (ms)	49.84	18.16
I_{beam} (mA)	217	423
(ΔQ_x SC)	0.0146	0.0040
(ΔQ_y SC)	0.0293	0.0081
L_0 ($cm^{-2}s^{-1}\ 10^{29}$)	1.0	1.0

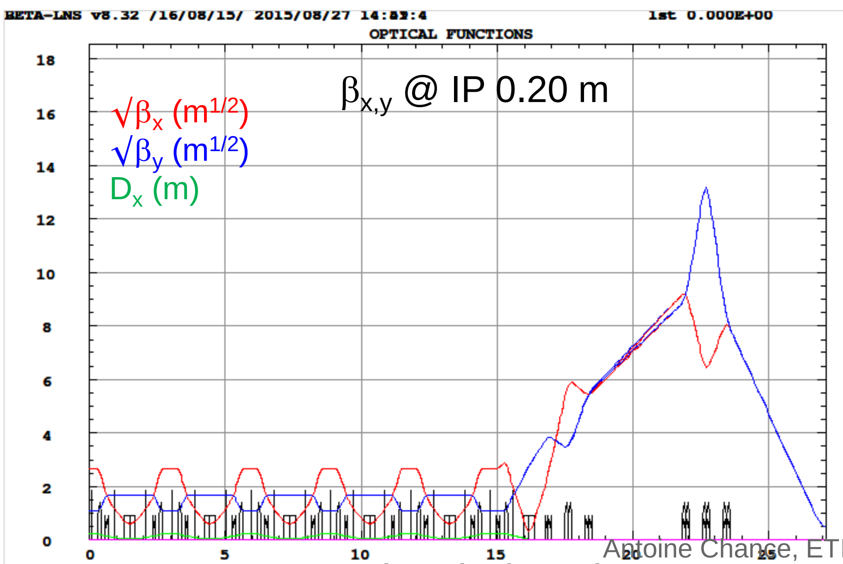
MBA LATTICE V28, 1.5 NM OPTICS



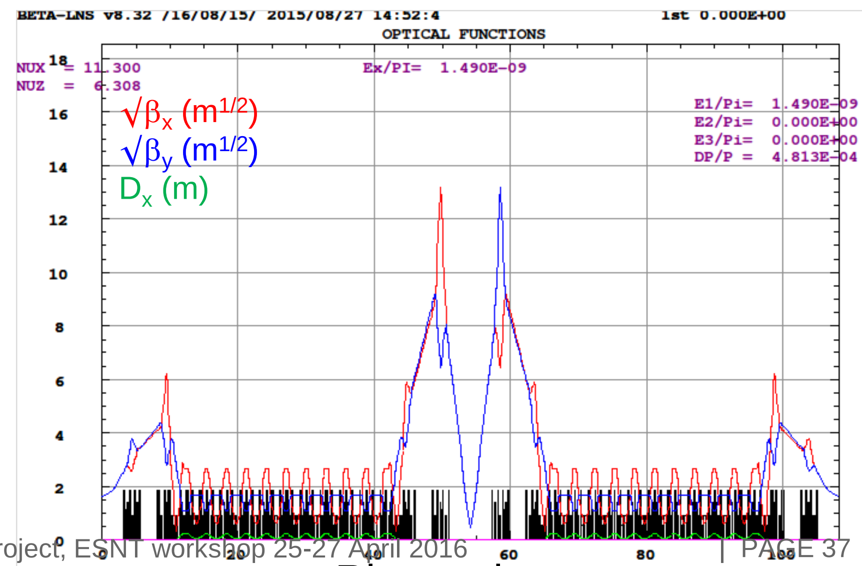
Arc cell optics (m)



Quarter ring (injection) optics (m)



Quarter ring (IR) optics (m)



Ring optics (m)

MBA LATTICE V28, 2.0 NM PARAMETERS

Circumference (m)	108.176
L bend (m)	0.4033
ρ bend (m)	1.5407
n bend=$-\rho/B_0\ dB_y/dx$	0
β_x , β_y @ IP (m)	0.15, 0.15
D_x max (m)	0.221
Q_x , Q_y	10.702,6.703
Q_x , Q_y arc cell	0.391, 0.256
$\xi_{x,y}=1/Q_{x,y}\ dQ_{x,y}/d\delta$	-3.50, -3.53
$l/(2B\rho)\ d^2B_y/dx^2\ (m^{-2})$	13.00,-18.25
t_{rev} (ns)	360.8
RF frequency (MHz)	352
h, n_{bunch}	127, 127
α_c	$2.05\ 10^{-3}$
N_{RI} (10^6)	1

E_c (MeV)	500	700
B field (T)	1.0846	1.5167
ε_x (nm)	1.09	2.14
σ_x @ IP (μm)	12.81	17.93
σ_y @ IP (μm) κ=.50	9.06	12.68
V_{RF} (kV)	87	135
δ_{RF} (%)	2.	2.
σ_δ (%)	0.0343	0.0481
σ_s (mm)	4.52	6.02
τ_x (ms)	102.91	37.50
τ_s (ms)	49.71	18.11
I_{beam} (mA)	233	458
(ΔQ_x SC)	0.0108	0.0030
(ΔQ_y SC)	0.0216	0.0059
L_0 ($cm^{-2}s^{-1}\ 10^{24}$)	1.	1.

To evaluate the effect three models of IBS growth rate was used

- The K. Bane high energy approximation

$$\frac{1}{T_\delta} \approx \frac{{r_e}^2 c\, N_e (log)}{32\, \gamma^3\, {\varepsilon_x}^{\frac{3}{4}}\, {\varepsilon_y}^{\frac{3}{4}}\, \sigma_s\, {\sigma_\delta}^3} \left\langle \sigma_H\ g_{bane}\left(\frac{a}{b}\right)\left(\beta_x \beta_y\right)^{-\frac{1}{4}} \right\rangle, \frac{1}{T_{x,y}} \approx \frac{{\sigma_\delta}^2 \left\langle H_{x,y} \right\rangle}{\varepsilon_{x,y}} \frac{1}{T_\delta}$$

- The MAX IV approximation

$$\frac{1}{T_\delta} \approx \frac{{r_e}^2 c\, N_e (log)}{32\, \gamma^3\, \varepsilon_x\, \varepsilon_y\, \sigma_s\, {\sigma_\delta}^2} \left(\frac{\varepsilon_x\, \varepsilon_y}{\langle\beta_x\rangle\langle\beta_y\rangle}\right)^{\frac{1}{4}}, \frac{1}{T_{x,y}} \approx \frac{{\sigma_\delta}^2 \left\langle H_{x,y} \right\rangle}{\varepsilon_{x,y}} \frac{1}{T_\delta}$$

- The modified Piwinski approximation (CIMP)

$$\begin{cases} \dfrac{1}{T_\delta} \approx \dfrac{{r_e}^2 c\, N_e (log)}{32\, \pi^{1/2}\, \beta^3\, \gamma^4\, \varepsilon_x\, \varepsilon_y\, \sigma_s\, \sigma_\delta} \left\langle \dfrac{{\sigma_H}^2}{{\sigma_\delta}^2} \left(\dfrac{g_{CIMP}(b/a)}{a} + \dfrac{g_{CIMP}(a/b)}{b} \right) \right\rangle \\ \dfrac{1}{T_x} \approx \dfrac{{r_e}^2 c\, N_e (log)}{32\, \pi^{1/2}\, \beta^3\, \gamma^4\, \varepsilon_x\, \varepsilon_y\, \sigma_s\, \sigma_\delta} \left\langle -a\, g_{CIMP}\left(\dfrac{b}{a}\right) + \dfrac{H_x\, {\sigma_H}^2}{\varepsilon_x} \left(\dfrac{g_{CIMP}(b/a)}{a} + \dfrac{g_{CIMP}(a/b)}{b} \right) \right\rangle \\ \dfrac{1}{T_y} \approx \dfrac{{r_e}^2 c\, N_e (log)}{32\, \pi^{1/2}\, \beta^3\, \gamma^4\, \varepsilon_x\, \varepsilon_y\, \sigma_s\, \sigma_\delta} \left\langle -b\, g_{CIMP}\left(\dfrac{a}{b}\right) + \dfrac{H_y\, {\sigma_H}^2}{\varepsilon_y} \left(\dfrac{g_{CIMP}(b/a)}{a} + \dfrac{g_{CIMP}(a/b)}{b} \right) \right\rangle \end{cases}$$

INTRA-BEAM SCATTERING (3)

Where :

$$\frac{1}{{\sigma_H}^2} = \frac{1}{{\sigma_\delta}^2} + \frac{H_x}{\varepsilon_x} + \frac{H_y}{\varepsilon_y}, a = \frac{\sigma_H}{\gamma}\sqrt{\frac{\beta_x}{\varepsilon_x}}, b = \frac{\sigma_H}{\gamma}\sqrt{\frac{\beta_y}{\varepsilon_y}}$$

$$H_{x,y} = \gamma_{x,y}\, {D_{x,y}}^2 + 2\alpha_{x,y}\, D_{x,y}\, {D_{x,y}}' + \beta_{x,y}\left({D_{x,y}}'\right)^2$$

$$(log) \approx ln\left(\frac{\gamma^2\, \varepsilon_x \left\langle\sigma_y\right\rangle}{r_e \left\langle\beta_x\right\rangle}\right)$$

$$g_{bane}(u) \approx 2\, u^{(0.021-0.044\, ln(u))}, 0.01 < u < 1$$

$$g_{CIMP}(u) \approx 2.691\left(1 - \frac{0.22889}{u}\right)\frac{1}{(1 + 0.16\, u)(1 + 1.35\, e^{-u/0.2})}, 0.1 < u < 10$$

INTRA-BEAM SCATTERING : L_{BUNCH} X 2

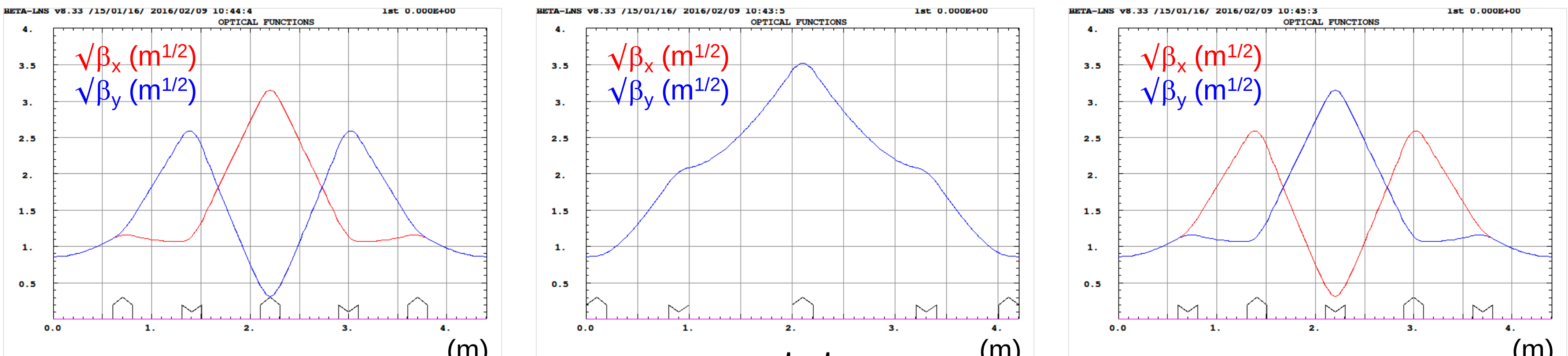
$N_{RI}=10^6$, $L_0= 10^{29}$ cm^{-2} s^{-1}									
Ec (MeV)	500			600			700		
Approximation	Bane	MAX IV	CIMP	Bane	MAX IV	CIMP	Bane	MAX IV	CIMP
1.0 nm tuning	**$\varepsilon_{x,0}$ = 0.59 nm, $\sigma_{\delta,0}$ = 3.4 10^{-4}**			**$\varepsilon_{x,0}$ = 0.85 nm, $\sigma_{\delta,0}$ = 4.1 10^{-4}**			**$\varepsilon_{x,0}$ = 1.16 nm, $\sigma_{\delta,0}$ = 4.8 10^{-4}**		
$T_{x,y}$ (ms)							231	227	181
T_δ (ms)							67	65	63
$\varepsilon_{x,y}$ (nm)							1.38, 0.69	1.38, 0.69	1.45, 0.58
σ_δ (10^{-4})							5.6	5.6	5.6
1.5 nm tuning	**$\varepsilon_{x,0}$ = 0.76 nm, $\sigma_{\delta,0}$ = 3.4 10^{-4}**			**$\varepsilon_{x,0}$ = 1.10 nm, $\sigma_{\delta,0}$ = 4.1 10^{-4}**			**$\varepsilon_{x,0}$ = 1.49 nm, $\sigma_{\delta,0}$ = 4.8 10^{-4}**		
$T_{x,y}$ (ms)				201	204	156	318	331	248
T_δ (ms)				67	68	62	94	98	90
$\varepsilon_{x,y}$ (nm)				1.54, 0.77	1.53, 0.76	1.74, 0.55	1.68, 0.84	1.68, 0.84	1.75, 0.75
σ_δ (10^{-4})				5.4	5.4	5.6	5.3	5.3	5.4
2.0 nm tuning	**$\varepsilon_{x,0}$ = 1.10 nm, $\sigma_{\delta,0}$ = 3.4 10^{-4}**			**$\varepsilon_{x,0}$ = 1.58 nm, $\sigma_{\delta,0}$ = 4.1 10^{-4}**			**$\varepsilon_{x,0}$ = 2.16 nm, $\sigma_{\delta,0}$ = 4.8 10^{-4}**		
$T_{x,y}$ (ms)				252	274	193	445	508	342
T_δ (ms)				81	87	75	130	147	125
$\varepsilon_{x,y}$ (nm)				2.1, 1.0	2.0, 1.0	2.3, 0.79	2.35, 1.17	2.32, 1.16	2.42, 1.08
σ_δ (10^{-4})				5.1	5.0	5.2	5.2	5.1	5.2

BBU OPTICAL SUPPRESSION SCHEME [1]
[1] D. DOUGLAS JLAB-TN-04-023

BBU threshold current $$I_{th} = \frac{2\, p_{beam} c^2}{e\, \omega_\lambda\, (R/Q)_\lambda Q_\lambda\, M^* \sin(\omega_\lambda\, t_{rec})}$$

$$M^* = M_{12} \cos^2\alpha + (M_{14} + M_{32})\, \sin\alpha\, \cos\alpha + M_{34} \sin^2\alpha$$

$$\begin{pmatrix} -I & 0 \\ 0 & i \end{pmatrix} \qquad \begin{pmatrix} 0 & A \\ A & 0 \end{pmatrix} \qquad \begin{pmatrix} i & 0 \\ 0 & -I \end{pmatrix}$$



rotator

With $I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$, $\quad i = \sqrt{-I} = \begin{pmatrix} 0 & \beta \\ -1/\beta & 0 \end{pmatrix}$, $\quad A = \begin{pmatrix} \sqrt{1-(b/\beta)^2} & b \\ -b/\beta^2 & \sqrt{1-(b/\beta)^2} \end{pmatrix}$

The transfer matrix is then $M = \begin{pmatrix} 0 & A \\ -A & 0 \end{pmatrix}$

$$M_{14} = -M_{32}, \qquad M_{12} = 0, \qquad M_{34} = 0$$

ERL MAGNETS

Arc dipoles	8
Magnetic length (m)	0.625
Deviation (rad)	$\pi/8$
Curvature radius (m)	1.591549
Field @ 530 MeV (T)	1.113

Injection/Extraction dipoles	8
Magnetic length (m)	0.3
Deviation (mrad)	8.281036
Curvature radius (m)	36.22735
Field @ 530 MeV (T)	0.05

Quadrupoles	81
Magnetic length (m)	0.2
Gradient @ 530 MeV (T/m)	19.6

RF modules	4
length (m)	11.2
Energy gain / module (MeV)	130
Frequency (GHz)	1.3