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Final Cooling For a High-Luminosity High-Energy Lepton Collider

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w/ Don Summers, Terry Hart (University of Mississippi), H.Sayed (BNL)

IPAC2015

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Outline

- Motivation
- Final Cooling for a Collider & Simulation
  - R. Palmer & H. Sayed
- Final scenario variations
  - w /D. Summers & T. Hart
  - round to flat and slicing ….
  - emittance exchange
  - bunch combination

P5 Goals: Long-Range Accelerator R&D

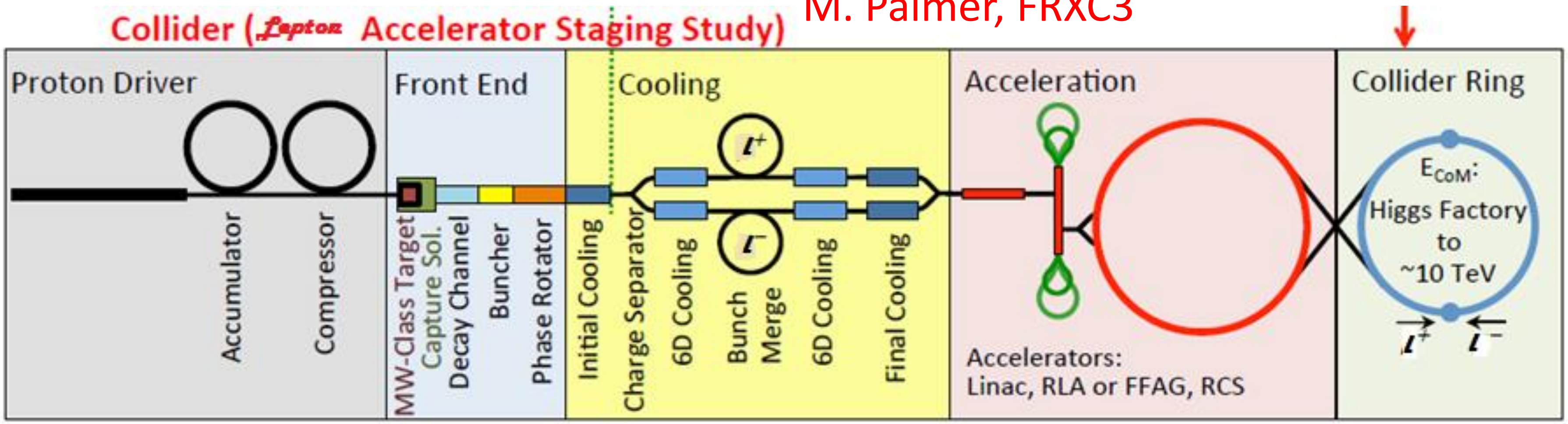
- “For e^+e^- Colliders the primary goals are:
  - improving the gradient and lowering the power consumption”
    - P5, Building for Discovery , p. 19 (May 2014)

P5 Goals: Long-Range Accelerator R&D

- "For e^+e^- Colliders the primary goals are:
  - improving the gradient and lowering the power consumption"
    - P5, Building for Discovery , p. 19 (May 2014)
- **Both goals are achieved by increasing the mass of the electrons**
  - Higher mass electrons will not radiate; enabling multipass acceleration; gradient is improved by number of turns
  - Non-radiating electrons, multipass acceleration, consume less power
- Changing the electron mass … (m_e is quantized)
  - 0.511, **105.6**, 1777 **MeV**
- 105.6 MeV is optimum for next generation e^+e^- Colliders
  - **requires $E' \gg m_e / c\tau_e = 0.16$ MV/m**

Towards multi-TeV lepton colliders

M. Palmer, FRXC3

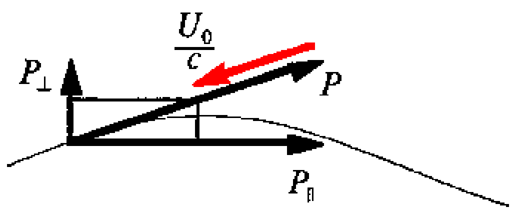


Parameter	Unit	Higgs factory	3 TeV design	6 TeV design
Beam energy	TeV	0.063	1.5	3.0
Number of IPs		1	2	2
Circumference	m	300	2767	6302
β*	cm	2.5	1	1
Tune x/y		5.16/4.56	20.13/22.22	38.23/40.14
Compaction		0.08	-2.88E-4	-1.22E-3
Emittance (Norm.)	mm·mrad	300	25	25
Momentum spread	%	0.003	0.1	0.1
Bunch length	cm	5	1	1
H. electrons/bunch	10^{12}	2	2	2
Repetition rate	Hz	30	15	15
Average luminosity	10^{34} cm^{-2}s^{-1}	0.005	4.5	7.1

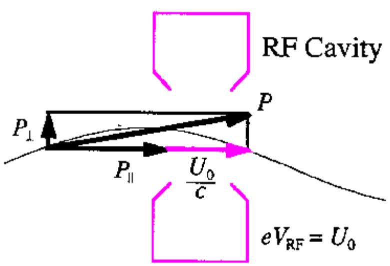
High-Luminosity Lepton Colliders need cooling

- light e^-
  – radiation damping

1. Lose $P_{e,t}$ in bends - synchrotron radiation

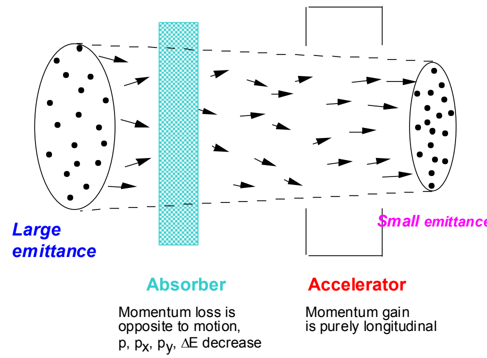


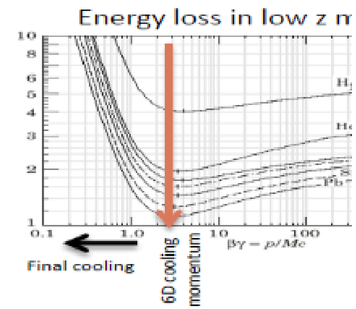
2. Regain only P_z in rf



- heavy e^-
  – "ionization cooling" ....

1. Lose $P_{l,t}$ in material –





2. Regain only P_z in rf

$$\frac{d\varepsilon_N}{ds} = -\frac{1}{P_\ell}\frac{dP_\ell}{ds}\varepsilon_N + \frac{\beta_\perp E_s^2}{2\beta^3 m_\ell c^2 L_R E}$$

Heating by multiple scattering

• Cooling for High Energy ›› Collider

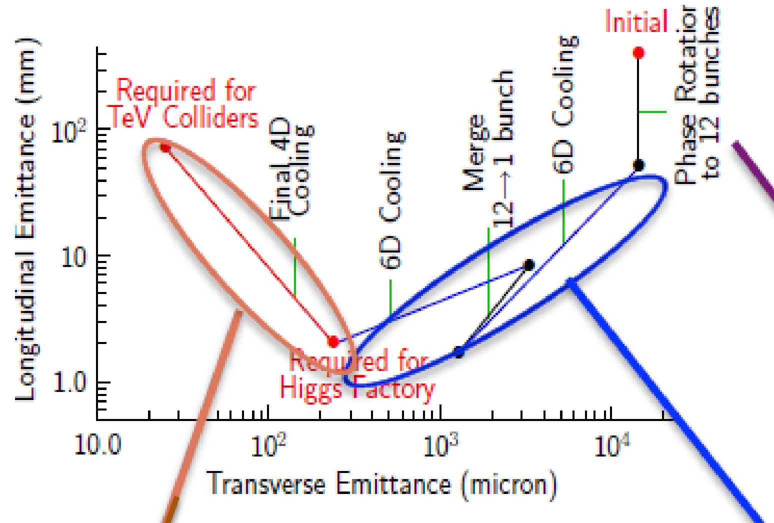
- Need Beam Cooling to reach high luminosity

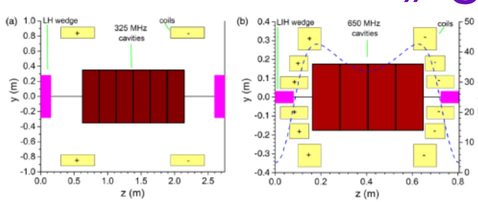
  Early stages: Cool $\varepsilon_{t,N}$ ~ 0.02 m -→0.0003 m

  - (10cm × 0.1 rad)→(1cm ×0.02 rad)
    - enough for 0.125 TeV Collider

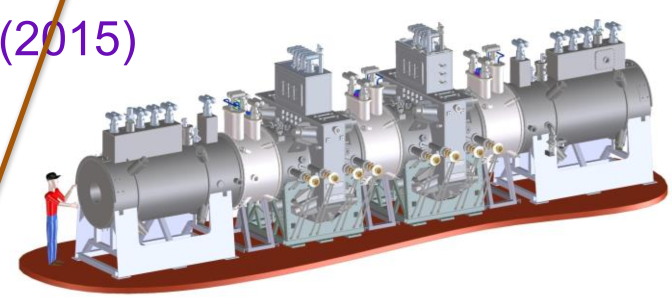
  – **Established by simulation, MICE**

  - uses 325/650 MHz rf
  - solenoidal focusing; B 2T →14T
    » Stratakis et al. PRSTAB 18, 031003 (2015)



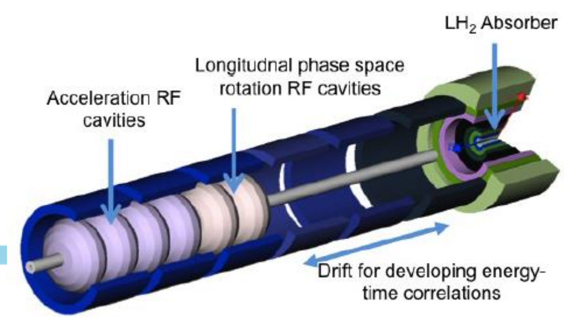


THPF042, IPAC14



– **Final Cooling more difficult:**

- more extreme parameters
- B → X0T ; f_{rf}: 20→4MHz; E→ 4 MeV



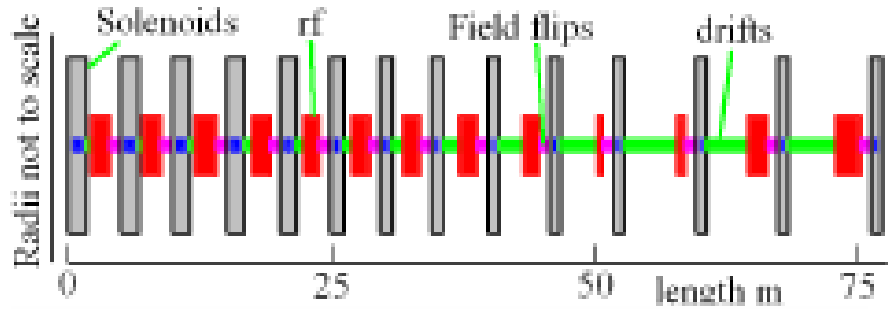
Final cooling baseline

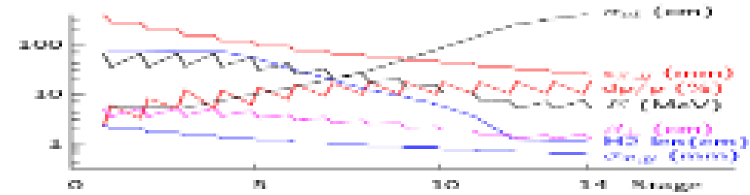
(R. Palmer et al. IPAC12)

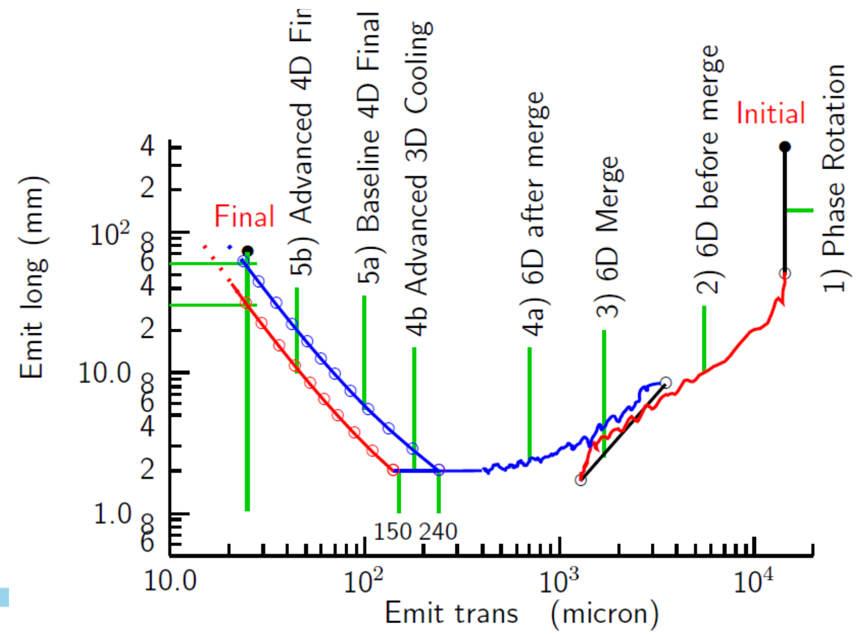
- **Baseline Final Cooling**
  - **solenoids, B → 30--50T**
  - **H_2 absorbers,**
  - **Low momentum**
  - **$\varepsilon_{t,N}$: 3.0 →0.3 × 10^{-4} m**
  - **ε_L : 1.0→70mm**
    - expensive emittance exchange

$$\varepsilon_{N,eq} \cong \frac{\beta_t E_s^2}{2\beta m c^2 L_R (dE/ds)}$$

$$\beta_t \cong \frac{2P_\ell \ (GeV/c)}{0.3B}$$







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Detailed simulation of final cooling

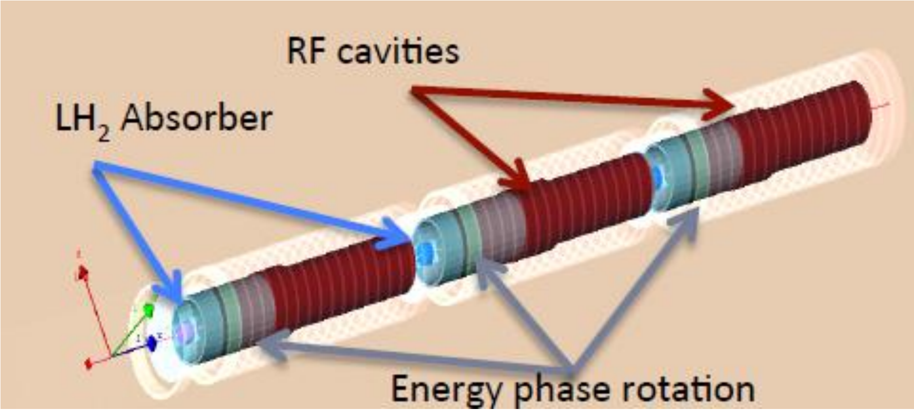
(H. Sayed et al. IPAC14)

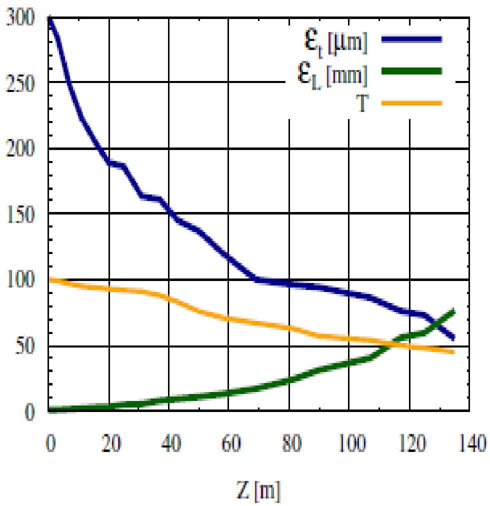
- G4Beamline simulation of final cooling scenario
  - System is ~135m long
  - $\varepsilon_{t,N}$: 3.0 →0.5 10^{-4} m
  - ε_L : 1.0→75mm

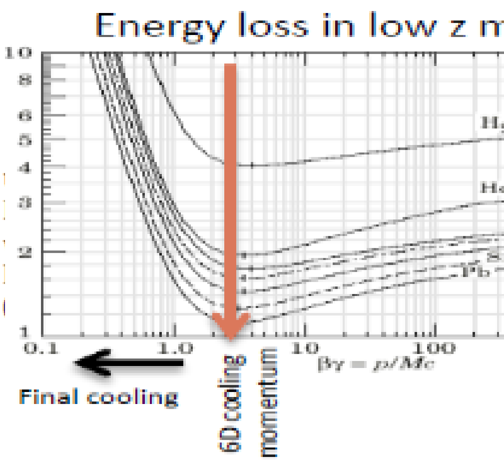
    P_l :135 → 70 MeV/c

    B: 25 →32 T; 325→ 20MHz
    - not quite specs
  - Transmission ~ 50%

- Predominantly $\varepsilon_{t,N}$ / ε_L emittance exchange







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Variant Approaches

- Keep P_l, B, E', f_{rf} within ~current technology
  - P > 100MeV/c; B~8➔15T; f_{rf} > ~100MHz
- Explicitly use emittance exchange in final cooling
  - Round to flat beam transport
  - bunch coalescence
  - thick wedge energy loss
  - Beam slicing and recombination
- Vary technology choices
  - "Flat beam" variations
  - solenoid → quad focussing
- Not (yet) including extreme methods
  - Li lens, parametric resonances

Round to flat transformation

Light electron source ~MeV

Cold source immersed in solenoid

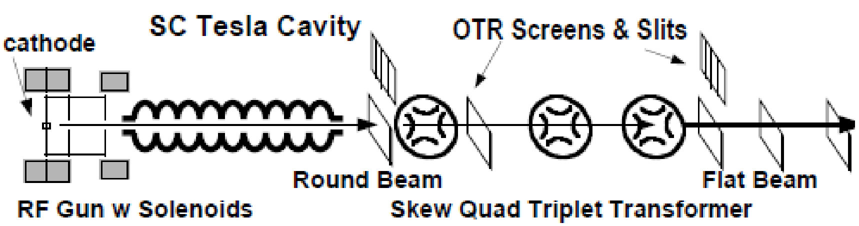
- large canonical L

solenoid to skew quad triplet

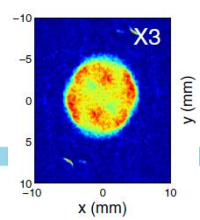
Changes “round” beam to flat

$$\varepsilon_{4D} = \varepsilon_T^2 = \varepsilon_+ \varepsilon_- = (\varepsilon_P + L)(\varepsilon_P - L)$$

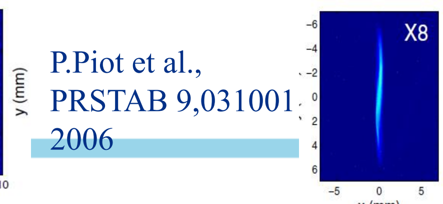
- Heavy Electron source ~100MeV
- Cooled within solenoids
  - cools transverse P_k
  - large canonical L (if no field flips)
- Can develop large difference in emittance modes

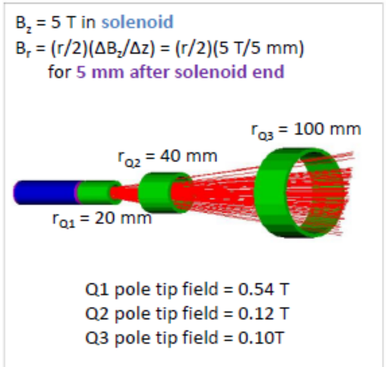


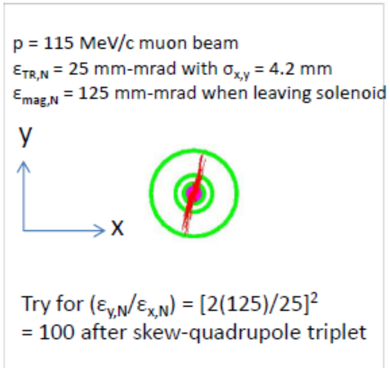
D. Edwards et al., Linac2000 p.122



P.Piot et al., PRSTAB 9,031001 2006







Beam Dynamics: Eigenmodes in solenoid

- **Round to Flat transform requires round beam formation in a solenoid**
- **In solenoid:**
  - **Coordinates are x, p_x, y, p_y**

$$p_x = k_x + \frac{eB}{2c} y \qquad p_y = k_y - \frac{eB}{2c} x$$

- $k_x = m\gamma v_x$

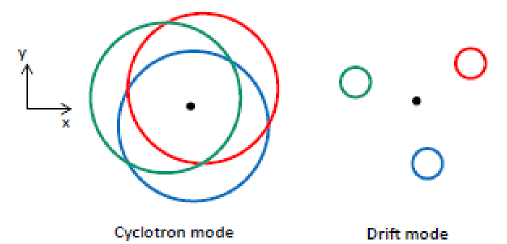
$$\begin{pmatrix} d_x \\ d_y \end{pmatrix} = \begin{pmatrix} x - \frac{c}{eB} k_y \\ y + \frac{c}{eB} k_x \end{pmatrix}$$

- **Alternative canonical coordinates:**
  - Cyclotron mode

$$\begin{pmatrix} \kappa_1 \\ \kappa_2 \end{pmatrix} = \sqrt{\frac{c}{eB}} \begin{pmatrix} k_y \\ k_x \end{pmatrix} = \sqrt{\frac{c}{eB}} \begin{pmatrix} p_y + \frac{eB}{2c} x \\ p_x - \frac{eB}{2c} y \end{pmatrix}$$

  - Drift mode

$$\begin{pmatrix} \xi_1 \\ \xi_2 \end{pmatrix} = \sqrt{\frac{eB}{c}} \begin{pmatrix} d_x \\ d_y \end{pmatrix} = \sqrt{\frac{eB}{c}} \begin{pmatrix} \frac{x}{2} - \frac{c}{eB} p_y \\ \frac{y}{2} + \frac{c}{eB} p_x \end{pmatrix}$$



Round to flat: (k, d) to (x, y)

References

A. Burov, S. Nagaitsev, A. Shemyakin, PRSTAB 3 094002 (2000)

A. Burov, S. Nagaitsev, Y. Derbenev, Phys. Rev. E 66, 016503 (2002)

K.J. Kim, PRSTAB 6 104002 (2003)

Cooling within solenoids

- Ionization cooling
  - Absorbers within solenoids
    - Cools k_1, k_2
  - Cyclotron mode is preferentially cooled
  - With

$$\ell = \frac{1}{2}\left\langle x p_y - y p_x \right\rangle$$

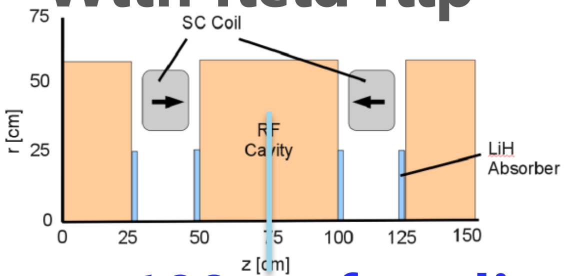
  - Typically (at $\varepsilon_x = \varepsilon_y = \varepsilon_t$)
    - $\varepsilon_1 \varepsilon_2 = \varepsilon_k \varepsilon_d = (\varepsilon_t - \ell)(\varepsilon_t + \ell)$

$$\varepsilon_1 \varepsilon_2 = \varepsilon_x \varepsilon_y - \ell^2$$

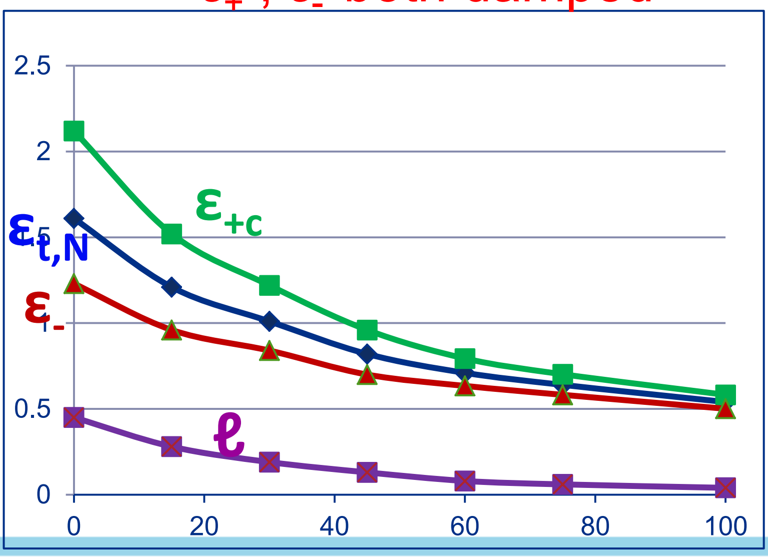
- With field flips:
  - k_1, k_2 and d_1, d_2 change identities with each flip
  - Both modes are equally damped
    - Angular momentum is damped
- Without field flips
  - One mode is preferentially cooled
  - Canonical angular momentum not damped

Example: Front End Cooling

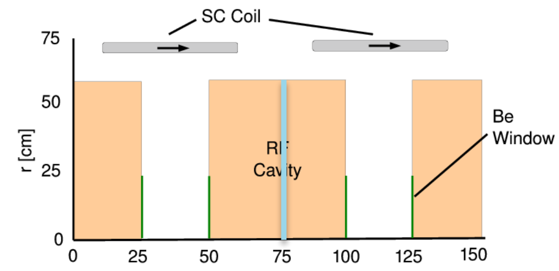
- **With field flip**



  - **100m of cooling:**
- $\varepsilon_{\perp,N}$: 0.016→0.0054
  - **ℓ damped:0.45→0.05**
    - ε_+ , ε_- both damped

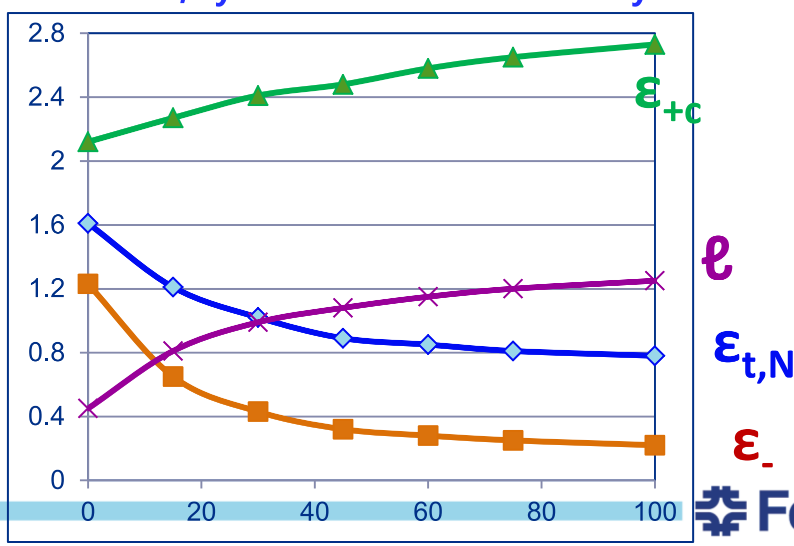


- **Without field flip**



- **$\varepsilon_{\perp,N}=(\varepsilon_+ \varepsilon_-)^{1/2}$:0.016→0.0078**
  - **ℓ increases:0.45→1.20**
    - $\varepsilon_+ / \varepsilon_-$ = ~15

k_x, k_y are damped d_x, d_y not damped



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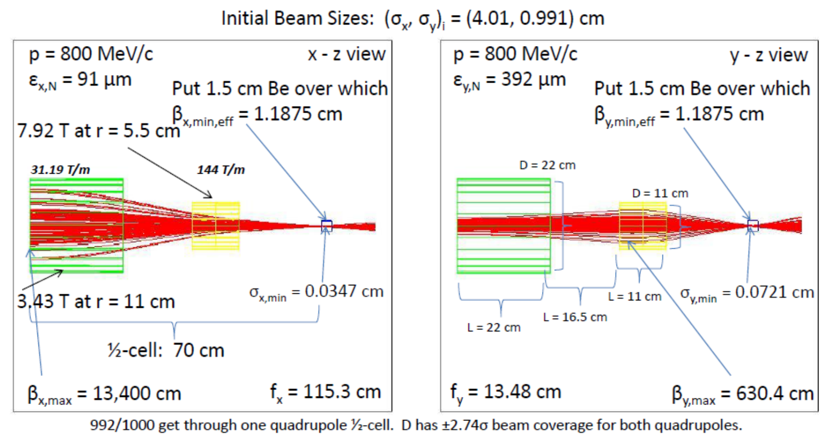
Variant: Quad focusing for final cooling

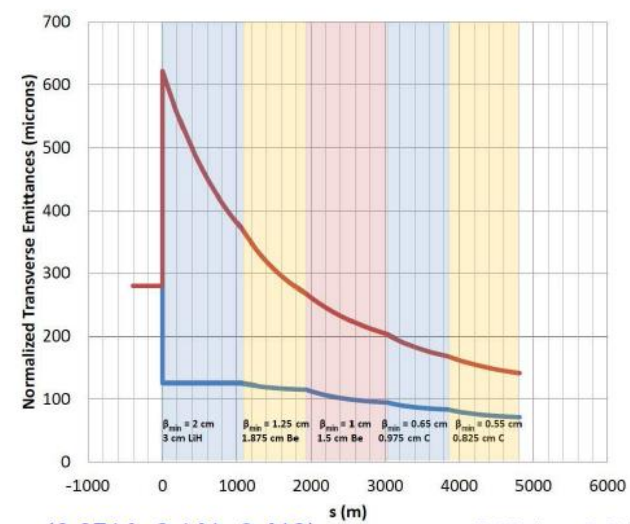
T. Hart, D. Summers TUPWI044

- Focusing onto short absorbers (LiH /Be)
  - Can obtain small β^*
- Quad focusing
  - use higher energy (0.8 GeV)
  - $\beta_x \neq \beta_y$ -- obtains flat beam ?
    - cools mostly 1-D ?
  - use B_{max}=8 T → 14T
  - cool in rings (multipass)

$$\varepsilon_{N,eq} \cong \frac{\beta_t E_s^2}{2\beta m c^2 L_R (dE/ds)}$$



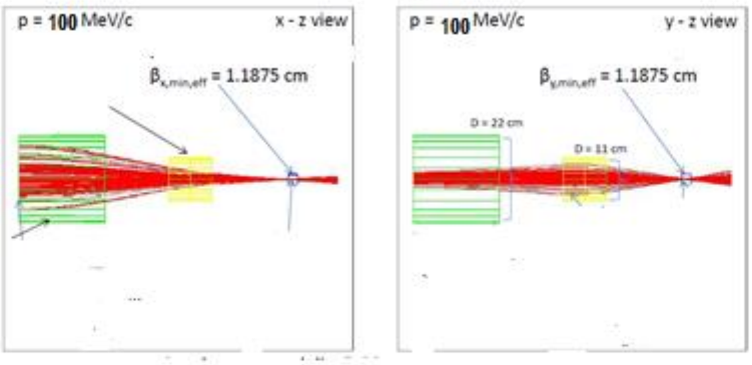
992/1000 get through one quadrupole ½-cell. D has ±2.74σ beam coverage for both quadrupoles.

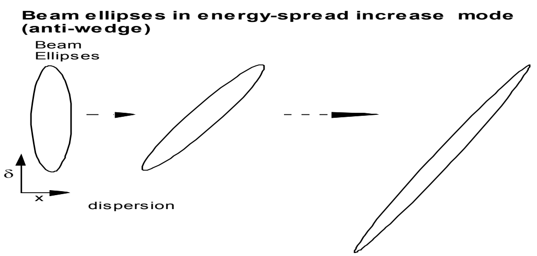


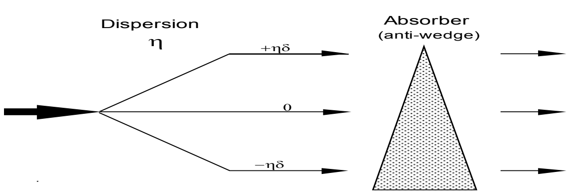
$\epsilon_{xyz} = (0.0714,\ 0.141,\ 2.418)$ mm. $\epsilon_{6D} = 0.024 < 0.044\ \mathrm{mm}^3$

Variant: “thick” wedge transform

- **If δp/p introduced by wedge >> $\delta p/p_{beam}$;**
  - **can get large emittance exchange**
    - exchanges x with δp (Mucool 003)
- **Example:**
  - **100 MeV/c; δp=0.5MeV/c**
    - $\varepsilon_{\perp} = 10^{-4}$m, β_0=1.2cm
    - Be wedge 0.6cm, 140° wedge
  - **obtain factor of ~5 exchange**
  - **$\varepsilon_x \rightarrow 0.2 \times 10^{-4}$m; δp=2.5 MeV/c**
- **Much simpler than equivalent final cooling section**







$$\varepsilon_1 = \varepsilon_0 \left[(1 - \eta_0 \delta')^2 + \frac{\delta'^2 \sigma^2}{\delta_0{}^2} \right]^{-1/2}$$

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Variant scenario: Cool, Round-to-flat, Slice, Recombine

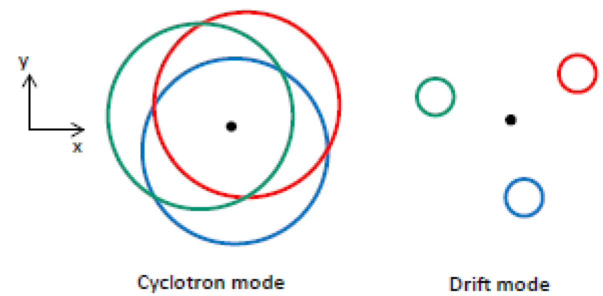
(w/ D. Summers, T. Hart)

1. Cool
   - Cool until system parameters are difficult
     - $\varepsilon_{x,y}$ (ε_t) → ~10^{-4} m, ε_L → ~0.004 m
2. Round to flat beam transform
   - ε_t → ε_x =0.0004; ε_y =0.000025m ?
3. Slice transversely in large emittance
   - using "slow extraction-like" septum to form 16 (?) bunches
     - ε_x =0.000025; ε_y =0.000025
4. Recombine longitudinally at high energy
   - bunch recombination in 20 GeV storage ring (C. Bhat)
     - ε_x =0.000025; ε_y =0.000025, ε_L=0.07m

1. Cool

- Start with "final cooling" scenario
  - or quad alternative or …
- Stop at ~step 5 – where parameters are still reasonable…
  - ε_t ~ 0.0001m
  - ε_L~ ~0.0025m
- Beam is at ~100--135 MeV/c
  - 66→ 40 MeV kinetic energy
- No field flips to obtain high-canonical momentum
  - Hisham has a simulation with
    - $\varepsilon_+ = 0.001$; $\varepsilon_- = 0.000025$
- No more cooling

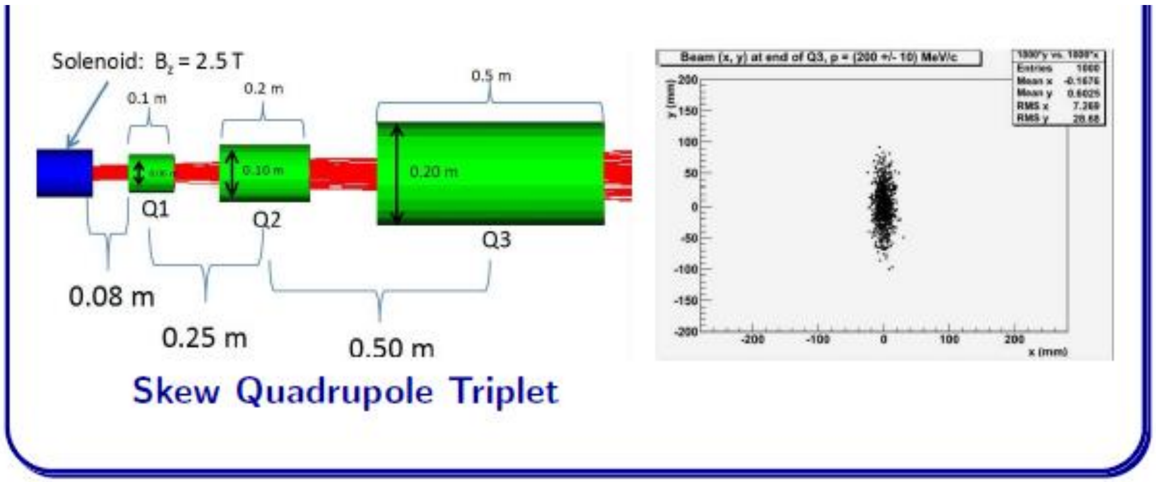
Stage	P_l (MeV/c)	Bmax (T)	$L_{abs}(H_2)$ cm	f_{rf} MHz
1	135	27	65	325
2	130	27	60	250
3	129	27	60	220
4	129	27	59	201
5	122	28	57	201
6	124	28	53	180
7	116	28	42	150
8	111	28	40	150
9	106	30	40	125
10	98	30	35	120
11	89.4	30	20	110
12	87.9	30	20	100
13	85.9	32	20	100
14	79.7	32	15	70
15	71.1	32	15	50
16	70	32	13	20
17	70	32	10	20



2. Round to Flat beam transform

Example:

- **Solenoid to quad +skew-quad transport**
- **Factor of 16 transform ratio:**
  - $\varepsilon_x \sim 4 \times 10^{-4}$ m, $\varepsilon_y \sim 2.5 \times 10^{-5}$ m
  - $\varepsilon_L \sim 2.5 \times 10^{-2}$ m



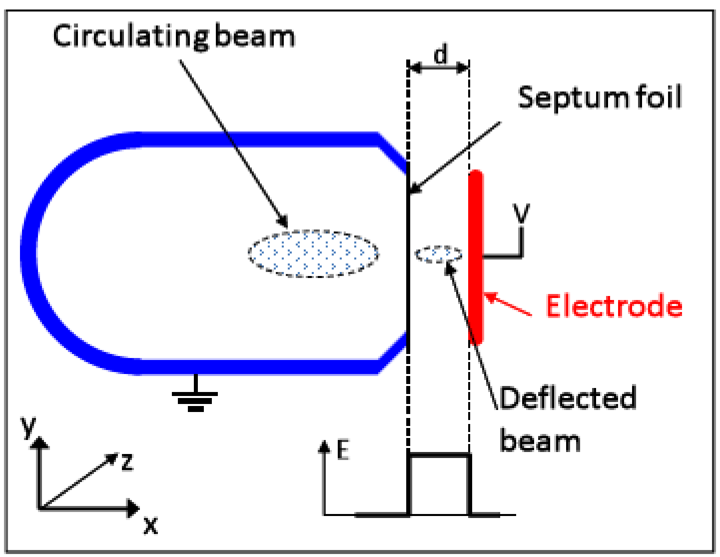
- **Accelerate to energy for next transformation**

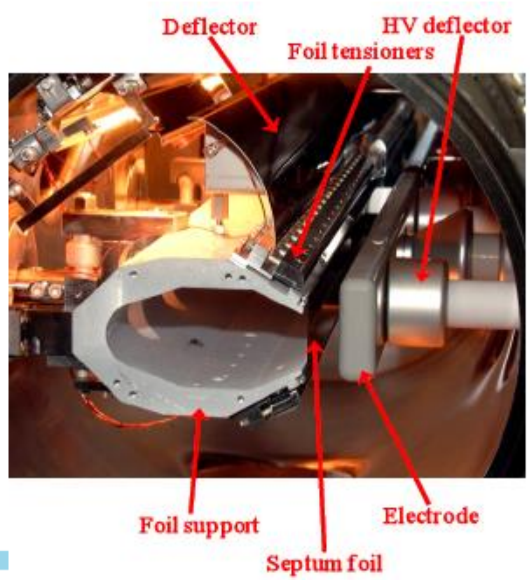
3. Slice transversely

match into Slicer optics (~linear or ring)

– small storage ring (?) with extraction optics
    - slicer is thin; slices in large emittance

- Slice beam transversely into n bunches
  – $\varepsilon_x \sim 4 \times 10^{-4}$ /16 → 2.5×10^{-5} m (for n=16)





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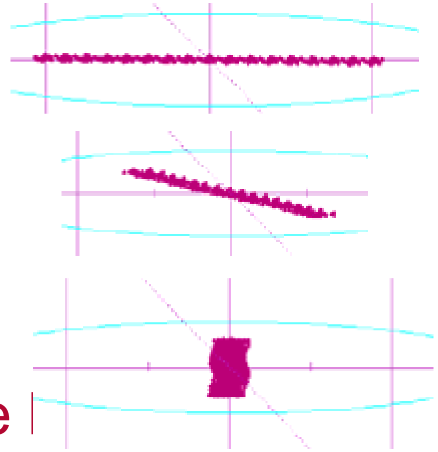
4. Recombine Longitudinally

- **Recombine Longitudinally**
  - **within High Energy Storage ring**
    - snap coalescence
      - modeled on pbar
    - Accelerate to higher energy
      - recombine train of bunches to single



- **Coalescence example** **(R. Johnson, C.Bhat et al. PAC07)**
  - **Inject 17 ℓ bunches into 21 GeV ring**
  - **Long wavelength rf gives each bunch a different energy**
  - **merge in 20 orbits (capture with short wavelength rf)**
    - emittance dilution, decay loss ~10%
- **0.25×10^{-4}m $\varepsilon_x \times \varepsilon_y$; $\sim 70 \times 10^{-2}$ ε_L ---**
- **HLHEC parameters**

Without Round to Flat transform….

- 1. Cool bunch to ~10^{-4}m ε_T
  - ~3×10^{-3} ε_L
- 2. Transverse slice to 10 bunches:
  - $10^{-4}\varepsilon_x \times 10^{-5}$m ε_y
  - Separated longitudinally
- 3. Accelerate as bunch train; recombine longitudinally
  - 10^{-4}m $\varepsilon_x \times 10^{-5}$m ε_y
  - ~3×10^{-2} ε_L
- Collide as flat beams;
  - luminosity ~ same as ε_t= ~3×10^{-5}

Flat beam Collisions ?

- IF x-y emittance product same as for baseline (round) Collider scenario
  - Can obtain ~ same luminosity

- Advantages
  - Chromatic correction easier
  - May be more natural result of final cooling
  - Flat beam could simplify beam/background collimation

- Some Disadvantages
  - hourglass effect is worse
  - loss of symmetry

Summary

- Final Cooling for High-luminosity HEC explored
  - Baseline approach possible; confirmed by simulation
    - inefficient, pushes state of art
- Variations can greatly improve the scenarios
  - **use more practical parameters**
    - **explicit emittance exchange procedures**
    - **Round to flat beam transformations, beam slicing,**
    - **bunch coalescing, quadrupole-based cooling,**
    - **flat beams**
  - **More extreme methods not (yet) included**
    - **Li lens, plasma lens, parametric resonance focusing**
      - **could greatly increase Luminosity from baselines**

- **Thank you for your attention !**

P5 → Heavy Electron Particle Accelerator Program

1. multi MW proton source
   – needs CD0

2. multi MW target facility
   – producing heavy leptons > 10^{21}/yr. ($\pi \rightarrow \ell + \nu$)

3. GARD- high B magnets, normal rf, SRF
   – HEPAP is only program that can use all of these …

4. LHC → HE/HL LHC → 100 TeV
   – need signs of new physics to build multiTeV HEC

"Use the Higgs as a tool for Discovery"

- Higgs Mass and Width can be directly measured at 125 GeV s- channel ℓ⁺ℓ⁻ Collider
  - mass and width, spin 0
- coupling to lepton mass
- Higgs and top mass
  - Do we need to know them to high precision ??

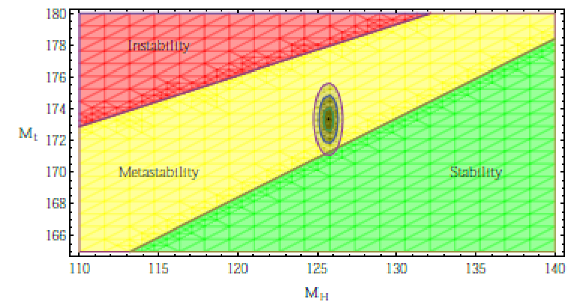


Figure 1: The stability phase diagram obtained according to the standard analysis. The $M_H - M_t$ plane is divided in three sectors, stability (green), metastability (yellow), and instability (red) regions (see text). The dot is for $M_H \sim 125.7$ GeV and $M_t \sim 173.34$ GeV (current experimental values). The 1σ, 2σ and 3σ ellipses are also shown, the experimental uncertainties being $\Delta M_H = \pm 0.3$ GeV and $\Delta M_t = \pm 0.76$ GeV.

δm_H to < 0.0001GeV

δm_T to <0.001 GeV

measured by spin precession