CERN

Proton EDM hardware challenges

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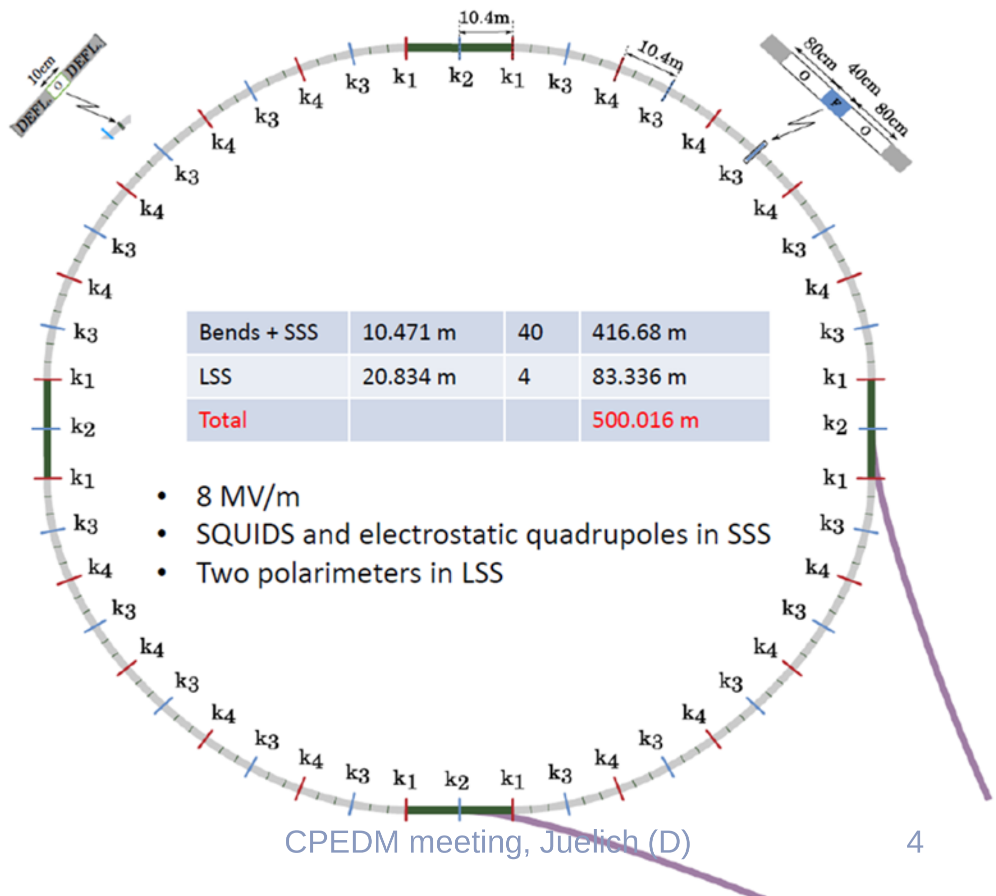
Outline

- Baseline lattice
- Bends
- Quadrupoles
- Injection devices, septa and fast deflectors
- Conclusion

Baseline lattice

Arc cell
- Drifts before and after bend 0.8 m (used for experiments and/or correctors/skew quad/sextupole/BPM)
- 2 bends of 4.16 m
- Drift between bends 0.1 m
- Quad 0.4 m
- Total cell length: 10.417 m

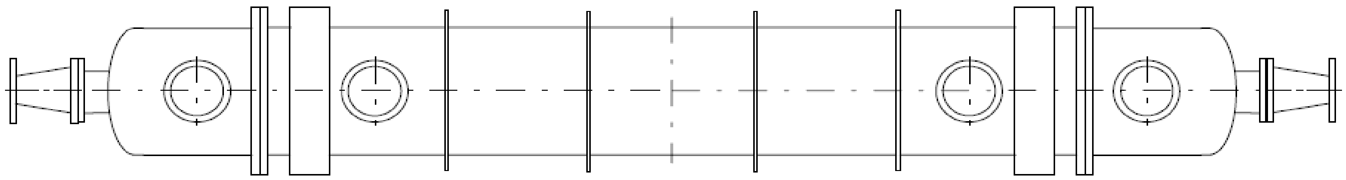
Beam
- Protons
- 700.74 MeV/c
- 232.8 MeV

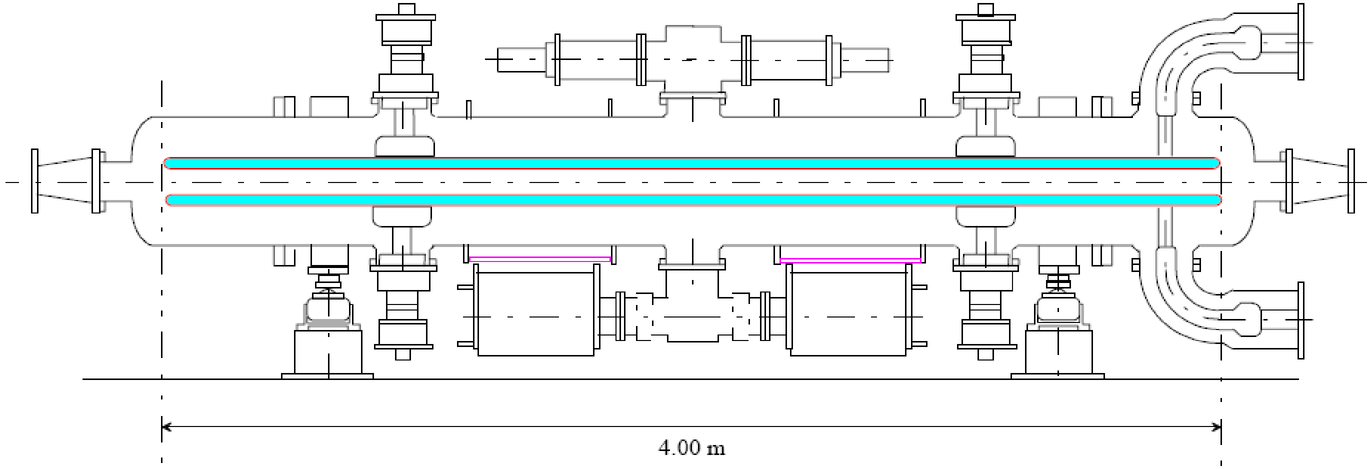


Bends + SSS	10.471 m	40	416.68 m
LSS	20.834 m	4	83.336 m
Total			500.016 m

- 8 MV/m
- SQUIDS and electrostatic quadrupoles in SSS
- Two polarimeters in LSS

Physical length vs Effective length

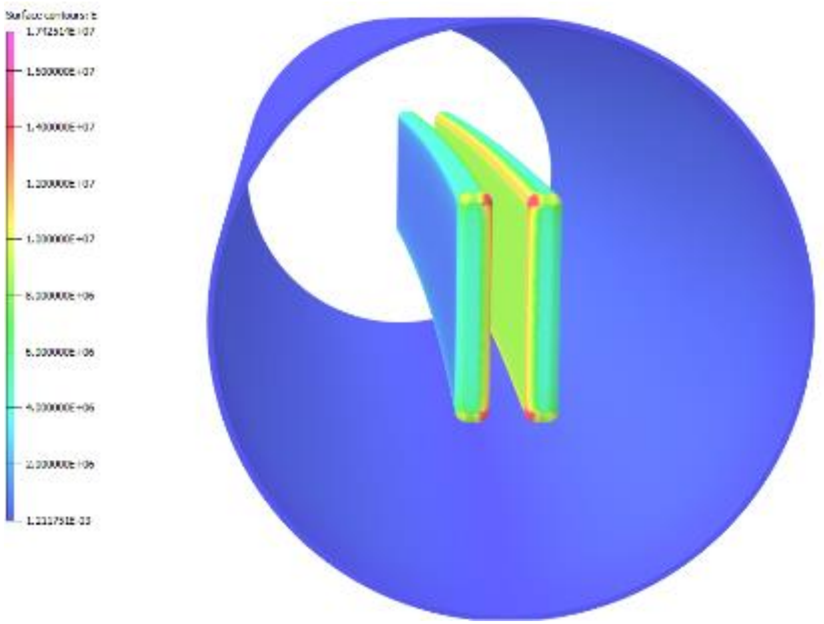




- SPS ZS septa: 3000 mm active length and 3378 mm device length; spacing > 870 mm
- LEP ZL: 4000 mm active length; 4500 mm device length; spacing > 650 mm

Note: Additional space would be needed for vacuum valves in case plug-in systems would be adopted to reduce down time in case of exchange due to failure

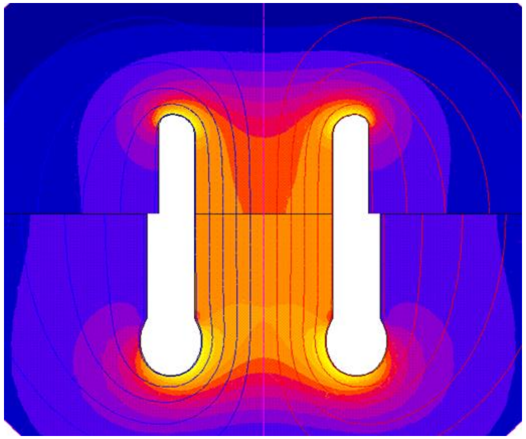
Bend requirements



- Total number of bends: 80
- $L_{physical}$: 4.1585 m
- L_{eff}: 3.7985 m
- Gap width: 30 mm
- Deflection angle: 78.54 mrad
- E_{gap}: 8.655 MV/m
- $V_{per\ polarity}$: ±130 kV
- Electrode height: 200 mm [1]
- Cylindrical electrodes [1]
- Vacuum: 10^{-11} mbar [1]
- Field homogeneity: 1 ppm on Ø20 mm [2]
- Power supply stability < 1.10^{-4} [2]
- Magnetic leak field: <10^{-11} T [3]

Bend challenges

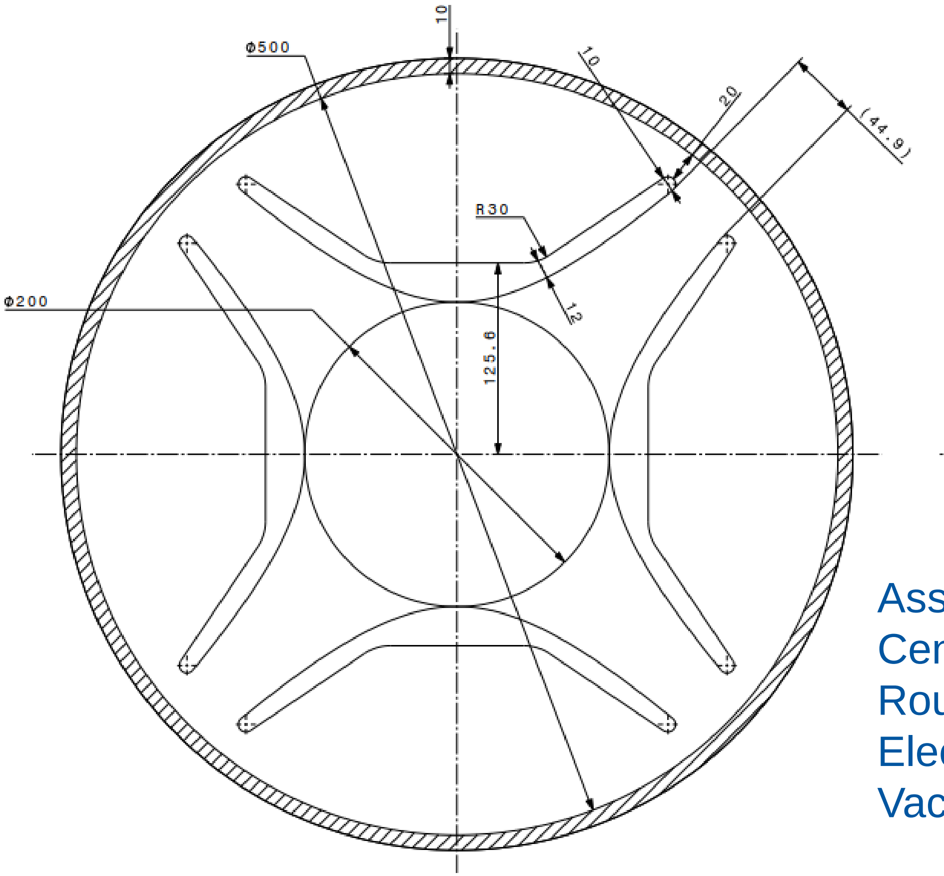
- Feasibility of 1 ppm field homogeneity tbc.
- Electrode profile needed to achieve required homogeneity causes higher fields on electrodes → need to reduce the average field assumed for the beam.
- E field high for use of Ti. Alternatives (TiN coated Al)?

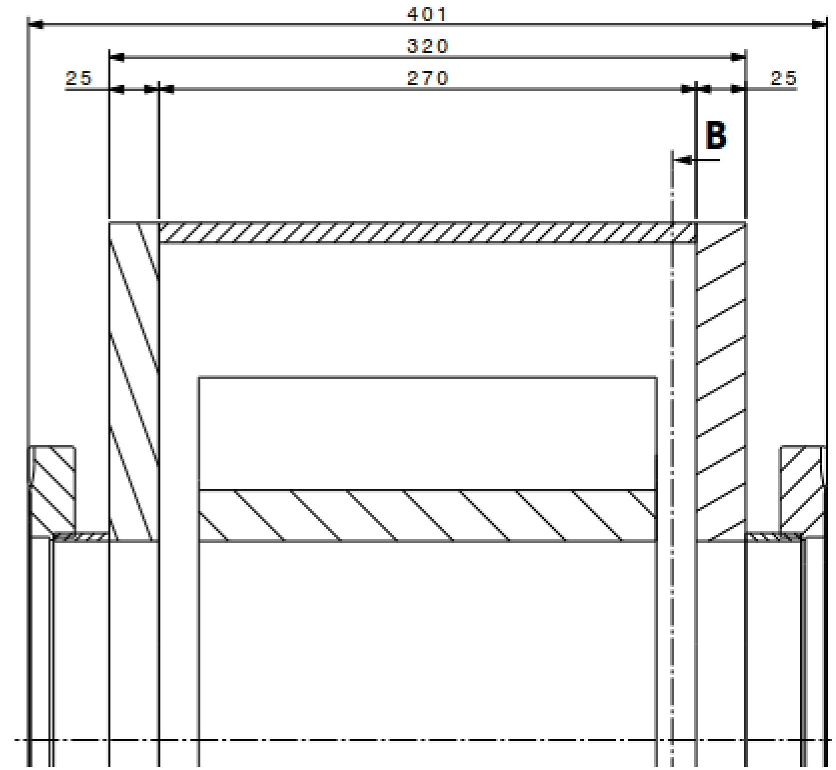


Bend challenges

- Non // plates induce skew quadrupolar effect → need to estimate achievable **electrode precision** to estimate requirements for skew quads in lattice.
- Does magnetic leak field requirement exclude **use of stainless steel**?
- To study if Al or Ti qualify as alternative construction materials.
- Assume bends at room temperature: **bake out** needed to obtain required vacuum.
- Assume all bends powered in // to reduce systematics, **HV conditioning** prior to operation needs to be studied.

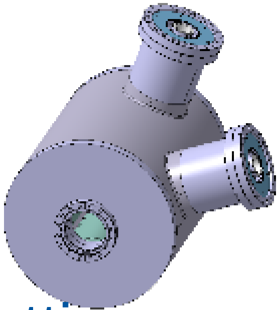
0.4 m Quad





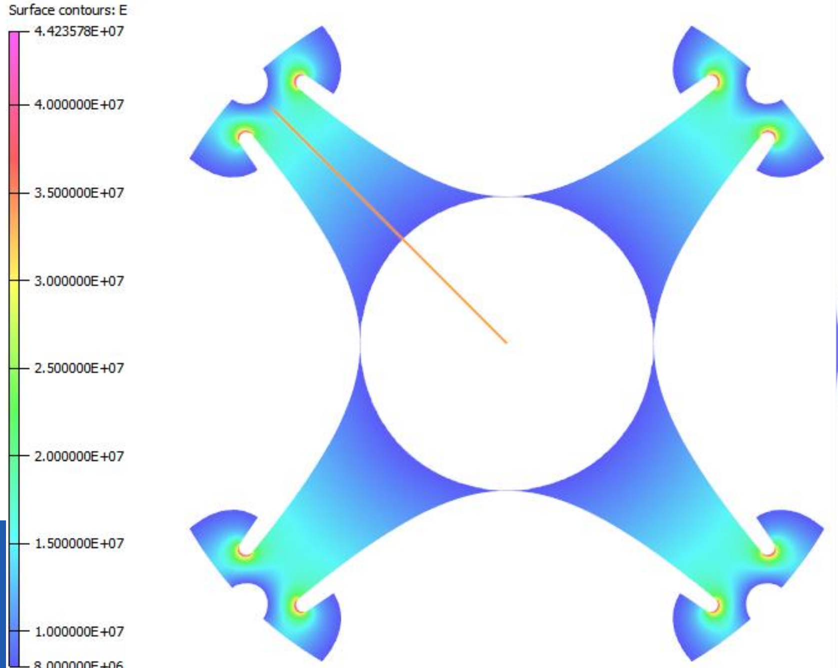
Assuming purely hyperbolic electrodes $x^2 - y^2 = \pm R$
Central radius $R = 100mm$
Rounded edges with $r = 5mm$
Electrode length $l = 230mm$, flange-to flange 401mm
Vacuum tank $ID = 500mm$

Quadrupoles

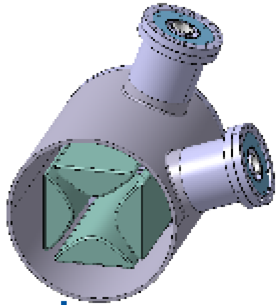


Field strength depends on strong or weak focussing lattice.

- Aperture (w x h): 30 x 200 mm^2
- k = 50 MV/m^2 (strong focussing), assuming L_{eff} = 0.4 m
- L_{ph}= 400 mm → $\underline{L_{eff} = 246\ mm}$ → k = 81 MV/m^2
- Knowing that $U = \pm\frac{1}{2}kR^2 \rightarrow \boldsymbol{U = \pm 404\ kV}$
- $E_{pole\text{-}tip}$: 8.1 MV/m
- $E_{pole\text{-}wings}$: >20 MV/m



Quadrupoles



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- Aperture (w x h): 30 x 200 mm^2
- k = 50 MV/m^2 (strong focussing), assuming L_{eff} = 0.4 m
- L_{ph}= 400 mm → L_{eff} = 246 mm → k = 81 MV/m^2
- Knowing that $U = \pm\frac{1}{2}kR^2$ → ~~$U = \pm 405\ kV$~~

a. U ≤ ±100 kV + R = 0.1 m → k < 20 MV/m^2 , E_{pole}= 2MV/m

b. L_{ph}= 0.8 m → L_{eff} = 646 mm → k = 30.8 MV/m^2, E_{pole}= 3.1 MV/m,

$$U = \pm 154\ kV$$

c. U=100 kV, k = 81MV/m2, L_{ph}= 0.4 m →R = 50 mm, E_{pole}= 4.1 MV/m

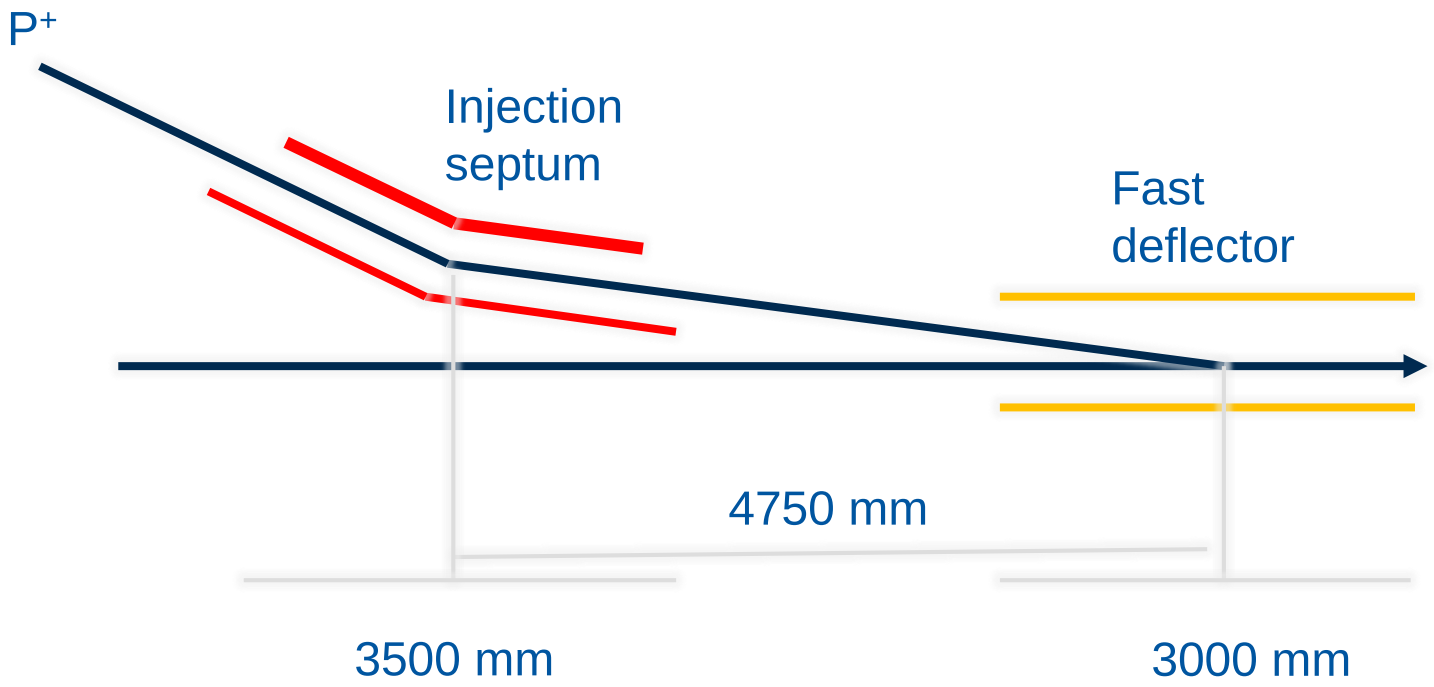
Quad challenges

- **Field homogeneity** dominated by end fields. Could be mitigated to some extend [4]. Need to determine minimum quad length that can achieve requirements
- HV **feedthrough integration** challenging for short quads.
- **Alignment precision** tbd, but assumed to be critical.
- Cryo quad makes alignment/**positioning** more complex, but **industrial solutions** may exist [5], using flexure guides and piezo actuators.
- Main quads to be powered in **4 families**; conditioning to be studied.

Courtesy WWW.JPE.NL

Injection straights

- Uses most of LSS

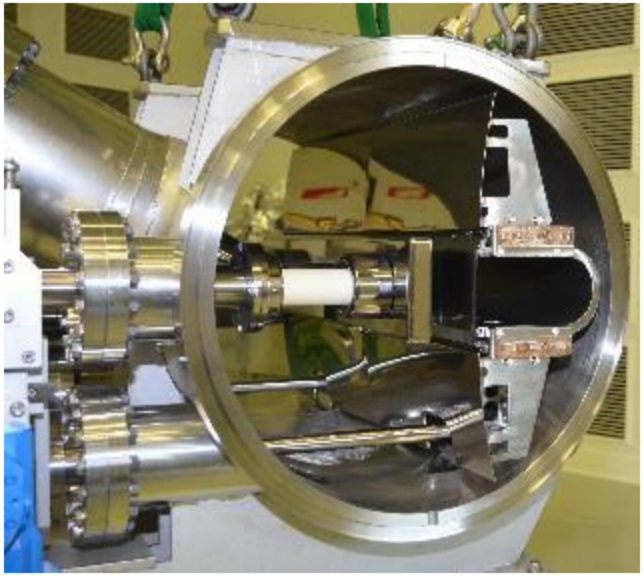


Injection devices

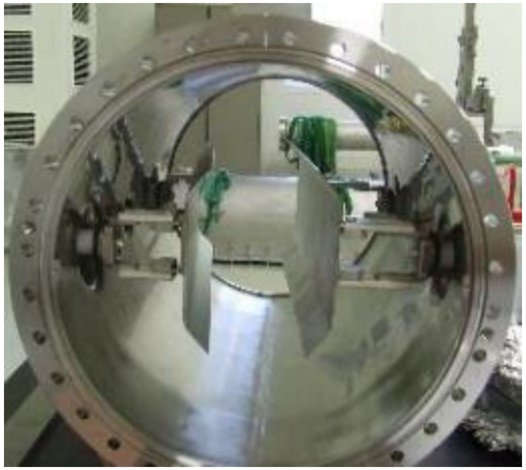
	Injection septum	Fast deflector
$L_{physical}$ [m]	3.5	3.0
Active length [m]	3.0	2.5
Deflection angle [mrad]	57.34	10
Gap width [mm]	30*	42.5**
Field [MV/m]	8.0	1.674
Radius of curvature electrodes [m]	52.32	-
Nominal electrode voltage [kV]	- 240	± 35.6
T_{rise} and T_{fall} (2‰ - 998‰) [μs]	DC	1.0
Capacitance per electrode (to gnd) [pF]	~ 660	< 500

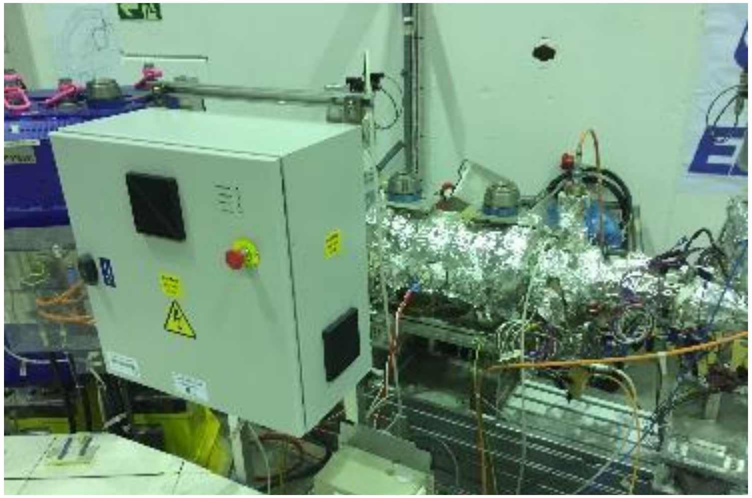
* Assuming curved or segmented septum and electrode
** Assuming parallel electrodes

Segmented septum, fast deflector examples



Segmented septum MedAustron





Fast deflector at CERN in ELENA

Open issues injection devices

Segmented foil septum v.s. curved wire septum

Feasibility of Fast Deflector pulse generator:

- rise and fall time feasibility to be validated
- voltage switch: not easily done using off the shelf switches (for example Behlke refreshes their switches at regular intervals even when switched off, and the electrodes wouldn’t remain grounded).
- Switches need to be located close to fast deflectors (0.5 m). Feasibility and reliability in the radiation to be studied.
- HV feedthroughs need development, not commercially available.

Alternative: stripline kicker(s)

- replacing fast deflector would reduce voltages to 30 kV (-20%) on plates, but at cost of added complexity.
- replacing the septum with a stripline kicker is not feasible.

Conclusion

- ✓ Electrode material will determine max. field strength, hence size of elements.
- ✓ Quad field strength to be quantified and feasibility of precision requirement to be determined.
- ✓ Lattice needs updating with:
  - ➢ Longer quads
  - ➢ Skew quads
  - ➢ Trim quads
  - ➢ Sextupoles
  - ➢ Vertical correctors
  - ➢ Present circumference seems optimistic
- ✓ Conditioning strategy for quads and bends to be studied.
- ✓ Injection equipment feasible in principle.
  - ➢ Fast deflector rise and fall time requirement to be validated.
- ✓ Use of stainless steel for construction desirable, but compatibility with magnetic leak field requirements tbc.

References

1. M. Lamont, “EDM strage ring – siting at CERN”, CERN EDM WG meeting, 1 June 2017
2. Y. Semertzidis, “All-electric versus combined field storage ring”, EDM kick-off meeting, CERN,13-14 March 2017
3. Reference to leak field level
4. R. Baartman, “Quadrupole shapes”, Phys. Rev. ST – Accel. Beams 15, 074002 (2012)
5. www.janssenprecisionengineering.com

Back-up slides

Bend

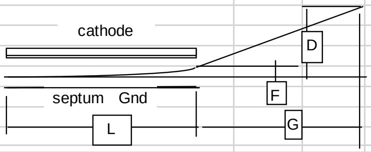
EDM Bend

particularités

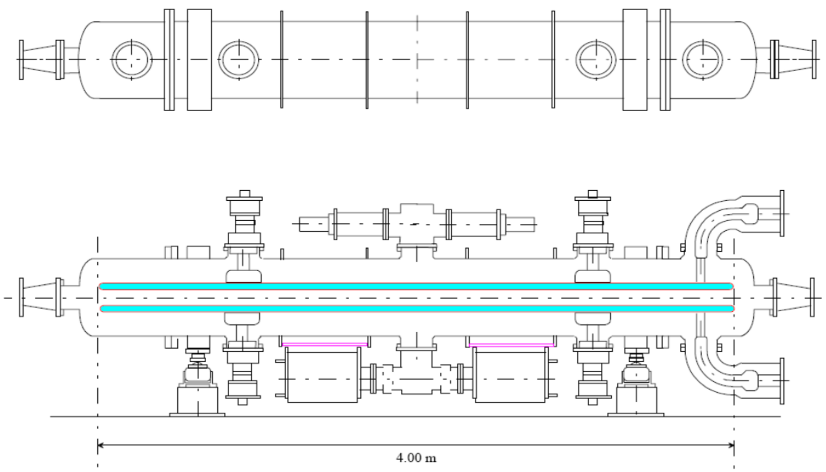
DONNEES		
particules		
type: electrons: e protons: p ions: i	p	
quant.mouvt: MV Energie cin: EC Rigidité faisc. BR	mv	
Quantité de mouvement p =	**0.7007**	**GeV/c**
Déflexion requise	**78.54**	**mrad**
Gap entre électrodes	**30**	**mm**
longueur active du seperateur	**3798.5**	**mm**
Espace de glissement	**0**	**mm**

RESULTATS	PROTONS	
Masse au repos mi	0.93826	GeV/c2
Energie cinétique	**0.2328**	**GeV**
Quantité de mouvement	**0.7007**	**GeV/c**
charge	1.00000	e
beta	0.5984	
gamma	1.2481	
beta*gamma	0.7469	
Brho	**2.3374**	**Tm**
Champ Electrique	**8.670**	**MV/m**
Tension entre électrodes	260.1	kV
Voltage per polarity	**130.0**	**kV**
Déplacement à la sortie du septum	149.17	mm
Déplac.après espace de glissement	149.17	mm
E.dl	32.933	MV
radius of curvature electrodes	**48.36**	**m**

longueur septum L	3798.5	mm
Espace de glissement G	0	mm
Déflexion sortie septum F	149.1667462	mm
Déflexion après espace de glissement D	149.1667462	mm



ZL active length 4000 mm; device length 4500 mm.

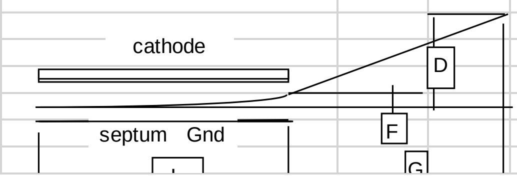


Fast deflector

EDM Fast deflector

particularités

DONNEES			RESULTATS	PROTONS		
particules			Masse au repos mi	0.93826	GeV/c2	
type: electrons: e protons: p ions: i	p		**Energie cinétique**	**0.2328**	**GeV**	
quant.mouvt: MV Energie cin: EC Rigidité faisc. BR	mv		**Quantité de mouvement**	**0.7007**	**GeV/c**	
Quantité de mouvement p =	**0.7007**	**GeV/c**	charge	1.00000	e	
			beta	0.5984		
			gamma	1.2481		
			beta*gamma	0.7469		
Déflexion requise	**10**	**mrad**	**Brho**	**2.3374**	**Tm**	
Gap entre électrodes	**42.5**	**mm**	**Champ Electrique**	**1.677**	**MV/m**	*defl*p*beta/long,*
longueur active du seperateur	**2500**	**mm**	Tension entre électrodes	71.3	kV	*tension*Gap*
Espace de glissement	**0**	**mm**	**Voltage per polarity**	**35.6**	**kV**	
T_{rise} and T_{fall} (2‰ - 998‰)	1.0	µs	**Déplacement à la sortie du septum**	**12.5**	**mm**	*angle defl * long /2*
eletrode height	100	mm	Déplac.après espace de glissement	**12.5**	mm	*angle defl * (long /2+gliss)*
			E.dl	**4.193**	**MV**	
			Capacitance per electrode	**5.56E-10**	**F**	
			longueur septum L	2500	mm	
			Espace de glissement G	0	mm	
			Déflexion sortie septum F	12.5	mm	
			Déflexion après espace de glissement D	12.5	mm	



Electrostatic injection septum

EDM Injection Septum					
Curved/segmented septum and electrode					
particularités					
DONNEES			**RESULTATS**	**PROTONS**	
particules			Masse au repos mi	0.93826	GeV/c2
type: electrons: e protons: p ions: i	p		**Energie cinétique**	**0.2328**	**GeV**
quant.mouvt: MV Energie cin: EC Rigidité faisc. BR	mv		**Quantité de mouvement**	**0.7007**	**GeV/c**
Quantité de mouvement p =	**0.7007**	**GeV/c**	charge	1.00000	e
			beta	0.5984	
			gamma	1.2481	
			beta*gamma	0.7469	
Déflexion requise	**57.34**	**mrad**	**Brho**	**2.3374**	**Tm**
Gap entre électrodes	**30**	**mm**	**Champ Electrique**	**8.014**	**MV/m**
longueur active du septum	**3000**	**mm**	**Tension entre électrodes**	**240.4**	**kV**
Espace de glissement	**0**	**mm**	**Déplacement à la sortie du septum**	**86.01**	**mm**
			Déplac.après espace de glissement	86.01	mm
eletrode height	100	mm	E.dl	24.043	MV
			radius of curvature electrodes	**52.32**	**m**
			Capacitance per electrode	6.655E-10	F
			longueur septum L	3000	mm
			Espace de glissement G	0	mm
			Déflexion sortie septum F	86.01	mm
			Déflexion après espace de glissement D	86.01	mm